DAHLGREN DIVISION
NAVAL SURFACE WARFARE CENTER
Dahlgren, Virginia 22448-5100

NSWCDD/TR-01/101

HUMAN-SYSTEMS ENGINEERING: UNDERSTANDING THE PROCESS OF ENGINEERING THE HUMAN INTO THE SYSTEM

BY DR. DANIEL WALLACE (WEAPONS SYSTEMS DEPARTMENT)

JOHN WINTERS MELISSA DUGGER
(BASIC COMMERCE AND INDUSTRIES, INC.)

JOHN LACKIE
(SONALYSTS)

TRISH HAMBURGER
(COMBAT SYSTEMS DEPARTMENT)

NOVEMBER 2001

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, search existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services. Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.		
1. AGENCY USE ONLY (Leave blank)	**2. REPORT DATE** November 2001	**3. REPORT TYPE AND DATES COVERED** Final
4. TITLE AND SUBTITLE HUMAN-SYSTEMS ENGINEERING: UNDERSTANDING THE PROCESS OF ENGINEERING THE HUMAN INTO THE SYSTEM		**5. FUNDING NUMBERS**
6. AUTHOR(s) Dr. Daniel Wallace (NSWCDD); John Winters and Melissa Dugger (BCI); John H. Lackie (Sonalysts); Trish Hamburger (NSWCDD)		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Commander Naval Surface Warfare Center Dahlgren Division (Code G53 and N05) 17320 Dahlgren Road Dahlgren, VA 22448-5100		**8. PERFORMING ORGANIZATION REPORT NUMBER** NSWCDD/TR-01/101
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES		
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		**12b. DISTRIBUTION CODE**

13. ABSTRACT (Maximum 200 words)

This report provides guidance on how human engineering practices can be better incorporated into systems engineering processes. The intended audience includes developers, engineers, and integrators who want to produce systems that will have greater capability through better consideration of all users. Four major impact areas for coordination of human engineering and systems engineering activities are discussed, and details of relevant interactions throughout the system development process have been identified. Information is provided linking the different actions to steps in different documented systems engineering standards and processes.

14. SUBJECT TERMS			**15. NUMBER OF PAGES**
Systems Engineering, Human-Centered Design, Human Engineering, Human Factors Engineering			82
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI std. Z39-18
298-102

FOREWORD

A true systems engineering approach will account for all pieces of the system being developed – the hardware, the software, and the people. The users and maintainers of the systems, however, are frequently underrepresented in system development. A primary goal of the ONR (Office of Naval Research)/SC-21 (Surface Combatant for the 21st Century) Science & Technology Manning Affordability Initiative was to promote the inclusion of human roles, capabilities, and limitations in the design process. This report is the direct result of a research effort in that area and is a follow-up to participation in the 1998 revision of the IEEE 1220 Standard for Application and Management of the Systems Engineering Process.

Progress in incorporating the users in the design of systems requires concentrated effort from both the systems engineering and human engineering communities. Common terminology and compatible processes must be developed. This report identifies key areas in which communication and cooperation between systems engineers and human engineers are critical. Without these important interactions, the systems being designed today will not fit the needs, capabilities, and limitations of the users and maintainers of tomorrow, handicapping our ability to meet affordability, flexibility, and knowledge superiority requirements for the 21st Century Fleet.

Approved by:

DR. KENNETH BAILE, Head
Combat Systems Department

CONTENTS

Section | Page

1 INTRODUCTION 1-1

2 MAJOR IMPACT AREAS 2-1
2.1 USER INVOLVEMENT AND REPRESENTATION 2-1
2.2 PARTICIPATION IN FUNCTION ANALYSIS 2-3
2.3 FUNCTION ALLOCATION DECISIONS 2-3
2.4 COMPATIBILITY OF MODELS 2-4

3 INTERACTION DETAILS 3-1
3.1 MISSION ANALYSIS 3-1
3.1.1 SELECTION OF COMPARISON SYSTEMS 3-2
3.1.2 SYSTEM USE SCENARIOS 3-3
3.1.3 USER ENVIRONMENT CHARACTERISTICS AND EFFECTS 3-5
3.2 REQUIREMENTS ANALYSIS 3-7
3.2.1 HUMAN ENGINEERING CONSTRAINTS 3-8
3.2.2 HUMAN PERFORMANCE REQUIREMENTS AND HUMAN ENGINEERING DESIGN REQUIREMENTS 3-9
3.3 FUNCTION ANALYSIS 3-11
3.3.1 FUNCTIONAL DECOMPOSITION 3-12
3.3.2 REVIEW OF FUNCTIONAL ARCHITECTURE 3-13
3.4 FUNCTION ALLOCATION 3-14
3.4.1 CONSIDERATION OF HUMAN ENGINEERING TECHNOLOGIES 3-15
3.4.2 EARLY IDENTIFICATION OF MANDATORY ALLOCATIONS 3-16
3.4.3 DEVELOPMENT AND APPROVAL OF FUNCTION ALLOCATION RECOMMENDATIONS 3-17
3.5 TASK DESIGN AND ANALYSIS 3-18
3.5.1 DEVELOPMENT OF THE TASK LIST 3-19
3.5.2 IDENTIFICATION OF TASK CHARACTERISTICS, INTERACTIONS, AND SEQUENCES 3-20
3.5.3 SELECTION OF MODELING TOOLS AND TECHNIQUES 3-21
3.5.4 TASK AND FUNCTION AUDIT 3-22
3.6 HUMAN INTERFACE AND TEAM DEVELOPMENT 3-22
3.6.1 POINTS OF HUMAN INTERFACE 3-23
3.6.2 SELECTION OF HUMAN INTERFACE AND TEAM GUIDELINES 3-24
3.6.3 DEVELOPMENT OF INTERFACE AND TEAM CONCEPTS OR DESIGNS 3-25
3.7 PERFORMANCE, WORKLOAD, AND TRAINING LEVEL ESTIMATION 3-26
3.7.1 INDIVIDUAL AND TEAM WORKLOAD AND PERFORMANCE ESTIMATION 3-27
3.7.2 TRAINING CONCEPT EVALUATION 3-29
3.7.3 TRADEOFF OF CONCEPTS AND DESIGNS 3-30
3.8 USER AND REQUIREMENTS REVIEW 3-31
3.8.1 COMPARISON TO HUMAN ENGINEERING REQUIREMENTS 3-32
3.8.2 USER REVIEW 3-33
3.8.3 RECOMMENDATION OF CHANGES TO REQUIREMENTS OR DESIGNS 3-34

4 BIBLIOGRAPHY 4-1

CONTENTS (Continued)

Page

APPENDIX A—RELATIONSHIPS BETWEEN INTERACTIONS AND SYSTEMS ENGINEERING PUBLICATIONS A-1

APPENDIX B—SUGGESTED REFERENCES B-1

DISTRIBUTION .... (1)

ILLUSTRATIONS

Figure		Page
1-1	Context of Interactions Between the Systems Engineer and the Human Engineer	1-2
1-2	Relationship Between Interaction Categories and the Systems Engineering Process	1-4

TABLES

Table		Page
3-1	Human Engineering Inputs and Products in Mission Analysis	3-1
3-2	Human Engineering Inputs and Products in Selection of Comparison Systems	3-2
3-3	Human Engineering Inputs and Products in System Use Scenarios	3-4
3-4	Human Engineering Inputs and Products in User Environment Characteristics and Effects	3-6
3-5	Human Engineering Inputs and Products in Requirements Analysis	3-8
3-6	Human Engineering Inputs and Products in Function Analysis	3-12
3-7	Human Engineering Inputs and Products in Function Allocation	3-14
3-8	Human Engineering Inputs and Products in Task Design and Analysis	3-19
3-9	Human Engineering Inputs and Products in Human Interface and Team Development	3-23
3-10	Human Engineering Inputs and Products in Performance, Workload, and Training Level Estimation	3-27
3-11	Human Engineering Inputs and Products in User and Requirements Reviews	3-32

EXECUTIVE SUMMARY

To be successful, a systems engineering effort must integrate relevant design disciplines and effectively balance available resources and required capabilities. The development of a system must include consideration of all its components and how to integrate them, including human users, operators, and maintainers. Since overall system performance capabilities are impacted by and depend upon human performance, good systems engineering should incorporate good human engineering practices.

Humans are included in systems for many different reasons – they are intuitive, flexible, and capable of many functions and tasks. But at the same time, humans are the most variable component of a system. But the limitations inherent in human cognitive and physical capabilities mean that people are commonly the least flexible and "designable" piece of the total system. Due to behavioral unpredictability and other difficulties in quantifying their performance and characteristics, humans are often neglected in design considerations. Such practices result in systems that are more difficult to use, more problematic for training, and less effective overall than they should be. Once such a system is produced, the human traits of flexibility and adaptability must be utilized to create and employ system deficiency "workarounds."

This report was produced to provide guidance on how human engineering practices might be better incorporated into systems engineering processes. The intended audience includes developers, engineers, and integrators who want to produce systems that will have greater capability through better consideration of all users – including operators, maintainers, and support personnel. The report is also intended for human engineers and human factors practitioners who want to be able to have a greater impact within the systems engineering process.

The process guidance documented within this report was primarily developed from task analyses of both systems engineering and human engineering processes. The systems engineering task analysis was performed first, using sources that included systems engineering standards such as IEEE 1220 and EIA/IS 632, the INCOSE (International Council on Systems Engineering) systems engineering handbook, and feedback from practicing systems engineers. The human engineering task analysis was documented in the context of the systems engineering task analysis. Tasks, decisions, and information that were common between the two processes served to identify areas in which interaction was required. The interactions that were identified through the task analyses can be grouped into the eight categories listed below.

1. *Mission Analysis*
2. *Requirements Analysis*
3. *Function Analysis*
4. *Function Allocation*
5. *Task Design and Analysis*

6. *Human Interface and Team Development*
7. *Performance, Workload, and Training Level Estimation*
8. *User and Requirements Reviews*

Although the human engineering team should have early and end-to-end involvement in the system development process, the level and criticality of human engineering participation will vary between the different design stages. Based on the information collected during the task analyses, four major impact areas for human engineering participation have been identified.

- User Involvement and Representation
- Participation in Function Analysis
- Function Allocation Decisions
- Compatibility of Models

These major impact areas are not meant to represent the bulk of the human engineer's work; they are intended to represent the most important ways in which the human engineer must interact with the systems engineer and other designers. They represent key interactions through which human engineering can be better integrated within systems engineering.

USER INVOLVEMENT AND REPRESENTATION

From the perspective of the user of a fielded product, the user interface *is* the rest of the system. If the user cannot find a particular function or a piece of information, then it may as well never have been developed. The best way to account for users in system design is to determine their needs, design the system to support completion of their tasks, and perform early and iterative evaluation with representative users. To accomplish this, scenarios for system use must be defined from the user's perspective and integrated into the design process. The best way to get feedback from representative users is to provide them with examples of how the system would be operated and what the user interface might include. User-oriented scenarios can be excellent vehicles for soliciting feedback during user reviews. Reviewers and potential users typically are able to provide better and more detailed feedback from a descriptive scenario than from a list of requirements or functional description. Such scenarios may also become the basis for comparative or evaluative testing of the system or the development of user models that describe user tasks, task sequences, and task interactions. In addition to scenarios, effective user involvement includes early and iterative usability and human performance testing throughout the development of the system and performance testing with representative users as part of the testing and evaluation processes. Subjective feedback from the user community is necessary, but objective performance testing is also needed to determine the true impact on system performance.

PARTICIPATION IN FUNCTION ANALYSIS

Since function decomposition and analysis are largely performed without regard to the allocation of the system's functions, they may be seen as areas that require little if any human engineering participation. The human engineer, however, can assist in identifying functions (such as life support of display capabilities) that must be included because of the presence of humans within the system. Additionally, much of the human engineer's later work in task design and analysis will be driven by the results of the function analysis. Any information on the required timing, sequence, or interaction of functions can be highly useful in the design of human tasks and jobs. Without human engineering participation, the function analysis is unlikely to contain sufficient details for functions to be allocated to humans, adversely impacting later designs or implementations.

FUNCTION ALLOCATION DECISIONS

Accurate allocation of functions between humans and automation requires the consideration of the capabilities and limitations of humans. Therefore, it is essential that the human engineers are part of the team. The earlier this participation occurs, the better the result is likely to be, as it can prevent improper design decisions that are costly or impossible to change at a later date. Such allocation decisions need to be an explicit part of the design process in order to optimize overall system performance. Using modeling techniques and sound design principles, the human engineer can provide reasonable estimations of what functions should and should not be allocated to humans. Making allocations as early as possible helps define the system to greater detail and also prevents these allocations from being made to the wrong system component.

COMPATIBILITY OF MODELS

Modeling and simulation techniques allow early evaluation of system designs, including information about how humans interact with one another or with the rest of the system. Such models can help systems engineers optimize the human performance within the system, but the main goal should be to set human performance to optimize the performance of the overall system. In order to accomplish this, the human engineering models need to be compatible with other models used in the design of the system. Compatibility can include transfer of static data between models as well as interactive executable models and simulations. Model compatibility enables accurate models of human performance and modeling of how human performance impacts the performance of the overall system.

For future complex systems to perform effectively, humans must be well integrated into the design process. To accomplish integration, the systems engineering effort must include communication with and integration of the human engineering community. Both communities must be able to work together and speak a common language in order to produce systems that are optimized to meet the needs of the users and operators.

1 INTRODUCTION

This report describes significant interactions that occur between human engineers and systems engineers during system development. These interactions include information that must be shared, decisions that must be made, and actions or decisions that require approval. The purpose of describing these interactions is to provide the reader with guidance on how human engineering activities may be better integrated with an overall system development or systems engineering process. It is intended for systems engineers and integrators who want to develop systems that will have greater consideration of users – including operators, maintainers, and support personnel. It is also intended for human engineers and human factors practitioners to help them have a greater impact within the systems engineering process.

The interactions were identified based on task analyses, documented in sets of operational sequence diagrams (OSDs), of both systems engineering and human engineering. The OSD format used to document these processes is a modification of the methodology and symbology of traditional OSDs.[1] OSDs are typically scenario-based and used for detailed human-machine interface analysis. They can be used to illustrate the transfer of information (input and output) and order of activities. The methodology used in this instance is intended to support higher-level descriptions of system operation and processes. For this use of the modified OSDs, the focus was on documenting the overall capability and recommended processes rather than a specific scenario.

The systems engineering and human engineering OSD sets were documented to support the development of the ONR (Office of Naval Research)/SC-21 (Surface Combatant for the 21st Century) Science & Technology Manning Affordability Initiative's Human Centered Design Environment (HCDE). The HCDE is a prototype for a collaborative design environment that supports the consideration and inclusion of human operators and users throughout the design process. Sources for the OSDs included standard systems engineering and human engineering processes, the INCOSE (International Council on Systems Engineering) Systems Engineering Handbook, and feedback from practicing systems engineers and human engineers. The OSDs describe the process in terms of task units, which typically include associated information requirements, decisions, and products. The diagrams for systems engineering were developed first, and the human engineering diagrams show how human engineering is performed in the overall context of systems engineering or system development. Both the task analysis diagrams and the information in this report focus on human engineering activities, although other human-system integration domains such as manpower, personnel, training, system safety, and

---

[1] Wallace, D.F.; Winters, J.J.; and Lackie, J.H., "An Improved Operational Sequence Diagram Methodology for Use in System Development," in *Proceedings of the Human Factors and Ergonomics Society*, San Diego, CA, 2000, pp. 6-505 – 6-508.

personnel survivability are addressed at times. The identification of common products, tasks, and information requirements permits the definition of interactions between the two processes (see Appendix A for URLs for the systems engineering and human engineering process task analyses).

The interactions are intended to be described in a stand-alone manner that does not require familiarity with any specified systems engineering or human engineering process. However, it should be noted that the perspective taken is generally from the systems engineer's point of view. In the detailed interaction descriptions, the context of the interaction within systems engineering is described first, followed by a description of the manner in which there is interaction with the human engineer. The systems engineering process information is included for context purposes only and is not intended to provide detailed and comprehensive coverage of systems engineering activities.

Throughout the descriptions, the terms "systems engineer" and "human engineer" are used. Although these are the singular forms, the terms could equally be pluralized or described as engineering teams. For the purposes of this report, the systems engineer is the individual(s) who has responsibility for the design of the system as a whole. Typically, the systems engineer's role includes programmatic responsibilities, but the emphasis in this report is on the technical role. The systems engineer may have a very active role in the definition of requirements or system functions, but his or her responsibilities change during the physical design of the system. At this point in the design process the purpose of the systems engineer is that of an integrator, and he or she is responsible for combining and deconflicting proposed designs submitted by engineers who specialize in particular disciplines or are responsible for particular subsystems. The human engineer plays one of these roles, specializing in job and task design and the interaction of humans with one another and with the rest of the system. His or her responsibility covers the human subsystems within the system to be designed. The relationships between the roles described in this report are illustrated in Figure 1-1. Although each of the relationships shown in Figure 1-1 are important, this report focuses on the relationship between the human engineers and systems engineers.

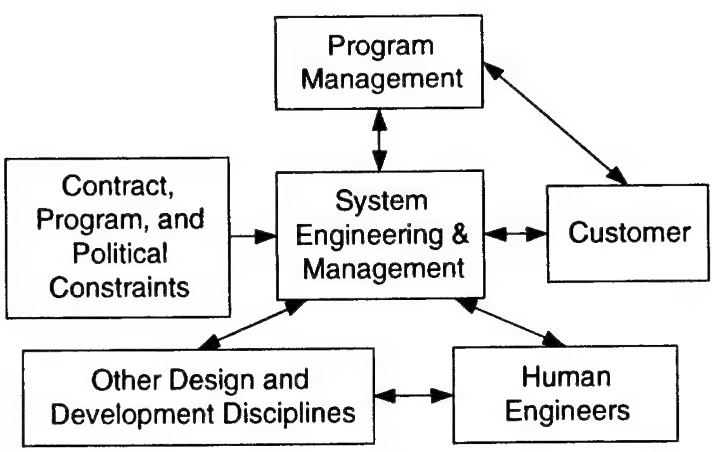

Figure 1-1. Context of Interactions Between the Systems Engineer and the Human Engineer

Section 2 of this report briefly discusses the major impact areas in which systems engineers and human engineers can interact. An interaction is considered significant if it has a relatively large impact on the design of the overall system or if its omission can lead to a drastic redesign of the system. An interaction could also be significant if the proper execution of the development process requires a great deal of iteration or communication between the systems engineer and the human engineer. The major impact areas represent abstractions or summations of recurring or important themes in the interactions that follow. The key issue for each of these impact areas and interactions is that integration of human engineering into the development process becomes more effective the earlier it is initiated.

The primary portion of this report, Section 3, describes the interactions in detail. The list of interactions has been grouped into eight major categories that are roughly grouped according to their sequence in standard systems engineering processes. The eight phases discussed in this report include:

1. *Mission Analysis*
2. *Requirements Analysis*
3. *Function Analysis*
4. *Function Allocation*
5. *Task Design and Analysis*
6. *Human Interface and Team Development*
7. *Performance, Workload, and Training Level Estimation*
8. *User and Requirements Review*

Figure 1-2 provides a context for how these eight categories relate to different top-level stages of standard systems engineering processes. In reviewing the contents of Section 3, it may be advantageous to refer back to Figure 1-2 to enable greater understanding of how each interaction fits into the overall process framework. The description of each interaction includes listings of relevant activities within different documented systems engineering processes. Listings of these relationships ordered by steps within the systems engineering processes are provided in Appendix A. The documents referenced include the following:

- IEEE 1220-1998, the Standard for Application and Management of the Systems Engineering Process;
- ANSI/EIA-632-1998, Processes for Engineering a System;
- the CMMI SE/SW v 1.02 capability maturity model; and
- Department of Defense Regulation 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs (MDAPs) and Major Automated Information System (MAIS) Acquisition Programs, June 2001.

References to relevant sections of the systems engineering OSDs produced within the HCDE project are also provided. Additional sources of information are listed in Appendix B.

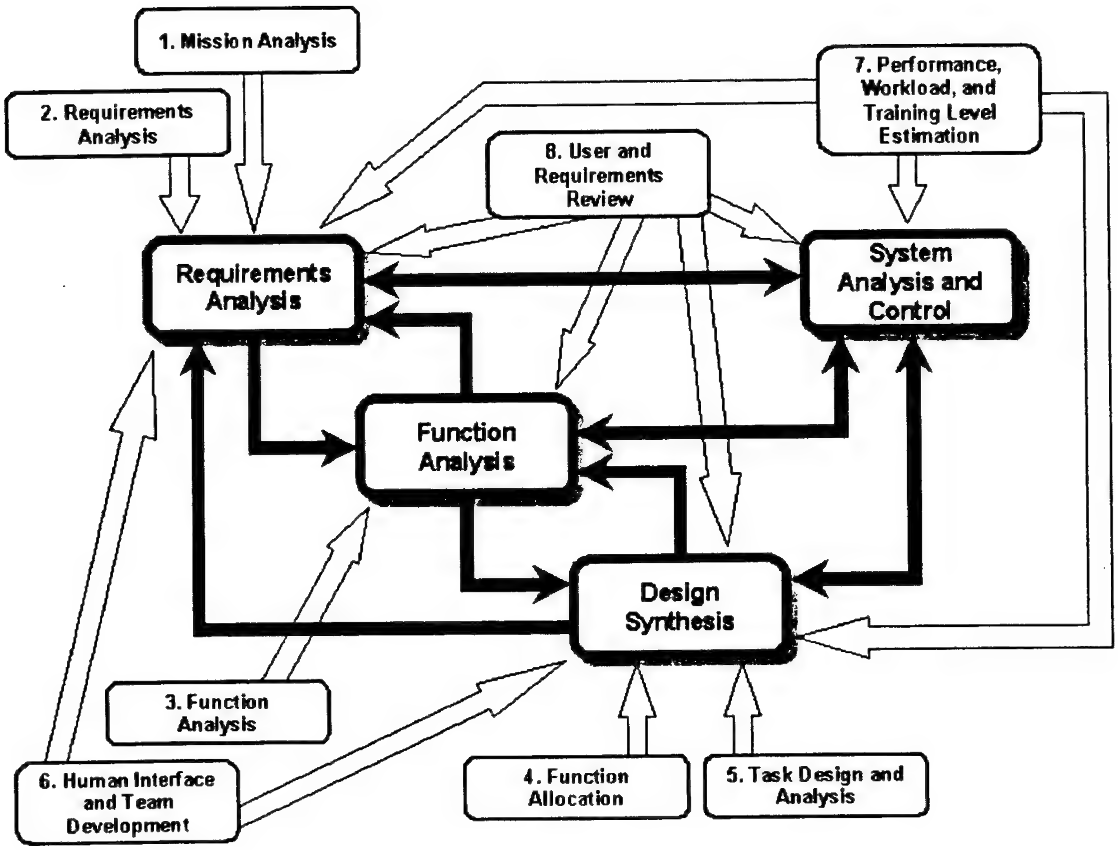

Figure 1-2. Relationship Between Interaction Categories and the Systems Engineering Process

2 MAJOR IMPACT AREAS

Based on the interactions described in this report, four major impact areas for human engineering participation have been identified.

- User Involvement and Representation
- Participation in Function Analysis
- Function Allocation Decisions
- Compatibility of Models

These interactions are not meant to represent the bulk of the human engineer's work; they are intended to represent the most important ways in which the human engineer must interact with the systems engineer and other designers. The interactions do not necessarily represent what is currently planned or carried out in system development, but they instead signify key interactions through which human engineering can be better integrated within systems engineering. Although the level of human engineering participation will vary with different design stages (e.g., concept definition versus detailed design), the human engineering team should have end-to-end involvement in the system development process. Initiation of human engineering activities only late in the process makes such analyses largely irrelevant due to the fact that time and resources will not be available to make anything but superficial design changes. User-inclusive requirements must be written in order to plan and conduct analyses that account for human performance and limitations within the context of the total system. Such analyses must be conducted and evaluated by those who understand how to translate them into effective design solutions.

2.1 USER INVOLVEMENT AND REPRESENTATION

By far the most critical area in which human engineering activities should be incorporated into the design process is the area of user involvement and representation. The human engineer needs to both facilitate feedback from users on concepts and designs as well as conduct user testing. The scope of this impact area ranges from the creation of accurate and relevant user-centered scenarios to solicitation of subjective feedback from users to analysis of the results of objective human performance testing.

The human engineer is often required to extend previous scenarios or build new scenarios in order to identify and provide details about how the operators and users will interact with the rest of the system. Different phases or modes of operation can be described, and scenarios may cover typical conditions, degraded conditions, emergency conditions, and worst-case situations. While many scenarios used in system development or testing may only cover conditions and events external to the system or actions at the total-system level, the human engineer is more interested in scenarios that describe how the system

will respond and operate from the user's point of view. Scenarios that describe only events and conditions external to the system can be expanded to include system operation and functionality from the perspective of the user. For example, a scenario that describes takeoff and cruising at 2500 feet at 150 knots can be expanded to include user tasks of reviewing map and weather information to select the best course to the destination.

Scenarios of system use are used to build task and job analyses for the operators and users and also to test designs and procedures. Since these scenarios are written from the perspective of the users and operators, they can be excellent vehicles for soliciting feedback during user reviews or as the basis for a user task model that describes user tasks, task sequences, and task interactions. Scenarios can be simply represented as written descriptions or storyboard sequences; therefore, they can be used in the early stages of system development. The detailed inner workings of the hardware and software do not need to be defined because such details are less relevant from the user's perspective. Representative users typically are able to provide better and more detailed feedback from a descriptive scenario than from a list of requirements or functional description. Regular user review throughout the development process provides a level of presence to the user, leading to a more detailed understanding of system operation and greater feedback on the design to the human engineer and the rest of the design team. Regular user reviews also provide user buy-in when the final system is delivered.

The review of user-centered scenarios with representative users or other appropriate individuals can provide feedback on the system's physical design, functional capabilities, or even performance requirements. Without this sort of review, the systems engineer can only assume that the system's requirements are compatible with the needs and limitations of the users or operators. Such reviews are a critical aspect of the validation of requirements and designs.

Due to training, experience, and related responsibilities, the human engineer is typically the designer who is best suited to coordinate user reviews of scenarios and system designs. To allow scenarios to be used in this way, the human engineer must have scenarios that accurately represent the interaction of personnel with the rest of the system. The human engineer must also be prepared to collect feedback on issues such as requirements and system functions in addition to control and display configurations. Understanding of these issues, such as how the system is intended to work and the proposed tasks for users and operators, is essential to comprehend the human roles in the overall operation, maintenance, and use of the system. With adequate interaction between the human engineer and the systems engineer, scenarios and user reviews can allow for early and rapid feedback on system requirements, functions, and designs.

In addition to review of user-centered scenarios, effective user review will also incorporate early and frequent usability and human performance testing. Static versions of the user interface can be used in conjunction with usage scenarios to obtain feedback before working prototypes are constructed. User review is not complete until

representative users have been employed in performance testing to ensure that the operational system will perform and interact with the users and operators as anticipated.

2.2 PARTICIPATION IN FUNCTION ANALYSIS

Since the decomposition of functions and definition of the functional architecture is largely performed without regard to the allocation of the system's functions, it may be seen as an area that requires little if any human engineering participation. There are, however, two distinct reasons for human engineering participation that can reduce the potential for having to change the function analysis at a later date. First, the human engineer can assist in identifying implied functions that must be included because of the presence of humans within the system. Some functions, such as life-support or communications, may be required regardless of the humans' assigned responsibilities. Other functions will become apparent once some preliminary allocations are made, including those allocations that may be assumed from the system's initial concept of operations. Second, much of the human engineer's later work in function allocation and in task design and analysis will be driven by the results of the function analysis. Information requirements, performance requirements, and decision requirements need to be defined to facilitate function allocation. Any information on the timing, sequence, or interaction of functions can be highly useful in the design of human tasks and jobs. Timing and overlap of tasks will influence workload, and unpredictable task sequencing can greatly decrease cognitive performance, such as accuracy of decisions or time to review and understand information. Without human engineering participation, the function analysis is likely to contain insufficient details for functions and subfunctions to be optimally allocated to humans. The human engineer is then left to make potentially incorrect assumptions about the information or to continue the function analysis through further decomposition or definition of the functions.

2.3 FUNCTION ALLOCATION DECISIONS

Since accurate allocation of functions to system elements requires consideration of the capabilities and limitations of humans, the participation of the human engineer is essential. Function allocation will be performed for all systems developed, either explicitly or by default. The key issue is whether or not the allocation process attempts to determine the best combination of humans and automation to accomplish the functions. The human engineer can provide reasonable estimations of what functions or portions of functions should and should not be allocated to humans. Until functions and subfunctions have been defined to significant detail, most functions will be allocated to "combinations" and not "fully manual" or "fully automated," but the human engineer can help to describe and model how the human and technology can interact to accomplish the function optimally.

The systems engineer and other participants in the function allocation process are likely to have a good idea of the capabilities and limitations of humans in general, but the

human engineer is likely to know more about or have better tools to estimate the specific capabilities and limitations of the intended users. The earlier this participation occurs, the better the result is likely to be, as it can prevent improper design decisions that are costly or impossible to change at a later date. The human engineer can assist in identifying functions or portions of functions that are required to have a particular allocation. Reasons for such decisions include functions that are absolutely beyond the capabilities of the anticipated users, assumptions made as part of the system's initial concept, and grouping of functions that will benefit job design. Making these mandated or intuitively obvious allocations as early as possible helps define the system in greater detail, narrows the design space, and also prevents these allocations from being made to the wrong system element or component.

2.4 COMPATIBILITY OF MODELS

Proposed designs of systems, subsystems, or components can be evaluated before the system is constructed through modeling. Although differing in scope or detail when compared to models of other disciplines, human engineering models provide useful information about how humans interact with one another and with the rest of the system. Such models can help the human engineer optimize the performance of humans within the system. Task network models can predict time or accuracy of task completion, anthropometric models can be used to determine reach limits or lines of sight over consoles, and cognitive models can estimate attentional demand or predict operator behaviors.

The main goal of the human engineer, however, should be to determine the required performance of the human in order to optimize the performance of the overall system. To accomplish this, the human engineering models need to be compatible with other models used in the design of the system. Compatibility can permit the interoperability of human engineering models with models built by other specialty engineering groups, and it may also allow human engineers to extend existing models. Without such compatibility, the human engineering models will not include an accurate representation of the system's hardware and software. Model compatibility facilitates accurate models of human performance and human performance impacts on the performance of the overall system.

3 INTERACTION DETAILS

This section of the paper outlines all of the systems and human engineering interactions uncovered from task analyses of the two processes. These descriptions are listed in an order compatible with their occurrence in systems engineering processes. Each interaction begins with contextual information to characterize the design process at the time of the interaction. Additional detailed information about the interaction follows, as well as the implications for the process. Finally, references to IEEE 1220-1998, ANSI/EIA-632-1998, the Engineering process area category of CMMI-SE/SW v 1.02, DoD 5000.2-R, and the Systems Engineering OSDs (SE OSDs) are provided.

3.1 MISSION ANALYSIS

The mission analysis phase of system development determines required system capabilities and the system's mission or purpose. During this phase, the boundaries of the system need to be identified, as do the interactions of the system with its environment and with other external systems. Scenarios or mission profiles are also created. Potential inputs and products of human engineering activities during Mission Analysis are listed in Table 3-1.

Although human engineering does not drive mission analysis, it is still critical due to its influence in determining human roles within the defined system and to the cost of significant changes at a later date. Problems that result from inadequate involvement

Table 3-1. Human Engineering Inputs and Products in Mission Analysis

Inputs	Products
• Requests for Proposals (RFPs)	• Descriptions of situations or events that will confront operators and maintainers, i.e., possible scenarios
• Planning documents	• List of system operational and maintenance requirements
• Systems requirements documents	• Descriptions of assumed operations
• Subject Matter Expert inputs	• List of operations that appear feasible
• Concept of operations	• Possible operations & maintenance thresholds
• Mission Needs Statement (MNS)	• Environmental factors possibly affecting system performance
• Lessons learned	• List of possible failures and effects
	• Human roles
	• Operator expectations

include deficiencies in scenarios and environmental descriptions. None of the system scenarios may include events from the user point of view, and they may not cover a sufficient range of events or conditions to adequately cover human involvement. Similarly, the full range of environmental conditions needs to be defined to enable the identification of the ramifications of environmental impact on system performance.

3.1.1 Selection of Comparison Systems

A frequently used approach in system development is comparison of the system under design to predecessor systems. While this technique is more straightforward for evolutionary designs, it may still be employed for systems that have no direct predecessor. All or part of the current system may be compared to all or part of some previous system that served a similar function, had a similar goal, or included similar components. This may be a formal process in which the performance and attributes of the predecessor system are quantified and set as a baseline upon which the new system must improve. It could also include a review of lessons learned from previous systems. Although it may be informal or even unintentional, some comparison is performed any time the developers have prior experience with the development or use of similar systems. Samples of potential inputs to this activity and products from the comparison with other systems are listed in Table 3-2.

Within the human engineering process, previously designed or built systems or subsystems are selected for comparison with the system under design. The system under development may have multiple comparison systems or a variety of comparison

Table 3-2. Human Engineering Inputs and Products in Selection of Comparison Systems

Inputs	Products
• Data on operability and usability of comparison system • Maintainability of comparison system • Staffing data on comparison system • Knowledge, skills, and abilities (KSAs) required of users of comparison system • Personnel opinions and problems encountered using comparison system • Training required for operators to reach target proficiency on comparison system • Historical data on errors, including design errors impacting human performance in comparison system • Workload analysis of users of comparison system • Lessons learned	• Critical incident analyses • Identification of environmental factors that may affect personnel • Preliminary predictions of workload and stress levels • Predicted knowledge, skills, and abilities (KSAs) required and their impact on staffing, training, and design • Predicted staffing • Identification of potential problem areas relating to operation and maintenance for focus in the new design • Predictions relating to allocation differences between old and new system

subsystems from different pre-existing systems. The human engineering practitioner may observe or otherwise analyze the performance of the comparison systems to establish design goals or performance requirements. Among the different types of data that may be collected are historical data, observational data, user data or feedback, and data from experimental prototypes. Information on past performance of multiple comparison systems may be used to select or narrow options for designs.

While the comparison systems must be similar to the current system in either mission or implementation, a system that is useful to the human engineer due to details of the human-machine interface may not be useful at the overall system integration level. The human engineer, however, will be required to address systems selected by the systems engineers or others as a baseline for comparison. The comparison could be based on similar missions, requirements, functions, tasks, users, or other factors. Systems or subsystems that the systems engineer considers relevant for the human engineer should be assessed by the human engineer to confirm their similarity and applicability to the system under design. The human engineer may find information on comparison systems selected by the systems engineers to be very useful in providing context or benchmarks for human performance measures. The human engineer may want to seek approval or concurrence from the systems engineer for the use of some comparison systems identified for system components under human engineering design responsibility. An early identification of comparison systems will allow the subsequent recommendations to have a more effective influence on design decisions.

IEEE 1220-1998: *6.1.2 – Define project and enterprise constraints*
6.1.3 – Define external constraints
EIA-632: *Requirement 4 – Process Implementation Strategy*
Requirement 13 – Information Dissemination
SE/SW CMM: *Requirements Management, SP 1.1-1 – Obtain an Understanding of Requirements*
Technical Solution, SP 1.1-1 – Develop Alternative Solutions and Selection Criteria
DoD 5000.2-R: *C5.2 – Systems Engineering*
SE OSDs: *SE110 – Define and Assess Operational Environment*

3.1.2 System Use Scenarios

Products such as system scenarios, design reference missions, and mission profiles or timelines are used by a variety of disciplines during system design. Information from these sources can be used to identify required interactions with external systems, determine functional requirements for a system, and establish performance requirements for interaction with external systems. Once designs are complete, such scenarios and timelines may be used to evaluate or validate system design options. Potential human engineering inputs and products in system use scenarios are shown in Table 3-3.

Table 3-3. Human Engineering Inputs and Products in System Use Scenarios

Inputs	**Products**
• System scenarios • Design Reference Missions (DRMs) • Mission profiles and timelines • Subject Matter Expert inputs • Concept of operations	• Estimates or verifications of staffing requirements • Estimates or verifications of workload and stress levels • Evaluation and ranking of predicted knowledge, skills, and abilities (KSAs) required and their impact on staffing, training, and design • Evaluation of the desirability and consequences of allocation different from comparison systems • Identification of potential problem areas relating to operation and maintenance for focus in the new design

In order to adequately account for the users or operators of the system under development, some scenarios must be defined from the user or operator perspective. System use scenarios describe, from the user's point of view, detailed events of the system mission, including identification of mission phases, mission time scale, and events external to (and their interactions with) the system. Scenarios selected by the human engineer should address cognitive and physical tasks and should emphasize impact on human performance, potential environmental effects, and safety. Additionally, they must be representative of the expected operating environment and threats to the system or mission. Scenarios of this type are necessary to perform job or task design, and they can be used to determine requirements for human-system interfaces. Scenarios from the user's perspective are powerful tools for eliciting user or subject matter expert feedback early in the design process. If use case models or user models are being developed, user-centered scenarios can assist in identifying user tasks, task sequences, and task interactions.

System use scenarios defined by the human engineer will often be extensions or subsets of scenarios developed or approved by the systems engineers, as would scenarios used within other design domains. Human engineers and other designs should use the same scenarios, with each group decomposing them to the appropriate levels of detail. The definition of system use scenarios will typically require assumptions on the part of the human engineer that further define the system. These scenarios, therefore, should be either approved or at least reviewed by the systems engineers and coordinated across design domains. The human engineer must ensure that system use scenarios accurately reflect a potential or achievable design and are consistent with other scenarios used in system development. Interaction in creating and refining these scenarios provides the systems engineering with scenarios that are more complete and provides the human

engineer with a better context for system operations. Scenarios must provide conditions that realistically tax human capabilities.

The development and subsequent use of system use scenarios is critical for the human engineer. Without valid scenarios to use in task design or defining user test situations, it will be difficult – if not impossible – to account for users and operators in the design process. As scenarios extend assumptions about system design, those assumptions must be verified or accepted by other disciplines. Collaboration with the systems engineer in scenario development will increase the probability that suggestions from user or subject matter expert reviewers will be accepted. Tasks that are specific to the use of interfaces or team interaction will have to be added to system use scenarios, and these extensions will also need to be verified with the systems engineer and other design disciplines.

IEEE 1220-1998: *6.1.4 – Define operational scenarios*
6.1.12 – Define modes of operations
EIA-632: *Requirement 4 – Process Implementation Strategy*
Requirement 16 – System Technical Requirements
Requirement 24 – Risk Analysis
SE/SW CMM: *Requirements Development, SP 1.1-1 – Collect Stakeholder Needs*
Requirements Development, SP 1.1-2 – Elicit Needs
Requirements Development, SP 1.2-1 – Transform Stakeholder Needs, Expectations, Constraints, and Interfaces into Customer Requirements
Requirements Development, SP 3.1-1 – Establish Operational Concepts and Scenarios
Requirements Development, SP 3.5-2 – Validate Requirements with Comprehensive Methods
Technical Solution, SP 1.1-2 – Develop Detailed Alternative Solutions and Selection Criteria
Technical Solution, SP 1.2-2 – Evolve Operational Concepts and Scenarios
Technical Solution, SP 2.2-3 – Establish a Complete Technical Data Package
Verification, SP 1.2-2 – Establish the Verification Environment
Validation, SP 1.2-2 – Establish the Validation Environment
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C3.2.3.2 – T&E Guidelines
C5.2.3.5.2.6 – M&S Support of SBA
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
SE OSDs: *SE110 – Define and Assess Operational Environment*

3.1.3 User Environment Characteristics and Effects

The design of the system must account for the environmental conditions under which the system will be employed. A wide range of environments is possible, and all relevant factors should be considered. Natural conditions such as weather, topology, time of day, and lighting conditions are of interest, as are conditions such as noise, vibration, and heat induced by the operation of the system. Threat conditions such as chemical or biological agents and use of lasers should also be identified. Once the conditions are identified, the

effects of those conditions and any resultant design constraints should be ascertained. Potential inputs and products for these activities are shown in Table 3-4.

Table 3-4. Human Engineering Inputs and Products in User Environment Characteristics and Effects

Inputs	Products
• Natural environmental conditions (weather, topology, time of day) • Induced environmental conditions (lighting, noise, vibration, and system induced heat) • System scenarios • Design Reference Missions (DRMs) • Mission profiles and timelines • Concept of operations • Required Operational Capability/ Projected Operational Environment (ROC/POE)	• Effects of predicted natural environmental conditions • Design constraints resulting from natural conditions • Effects of predicted system conditions • Design constraints resulting from system conditions • Strategies to mitigate environmental impact on users • User performance-shaping events and impact of those events

The human engineer will need to assess the environmental conditions catalogued by the systems engineers and determine whether or not all conditions that significantly affect humans have been identified. Operators and users must be shielded entirely from some environmental characteristics and other characteristics will influence their performance. The human engineer will need to quantify the effects of environmental characteristics on human performance and work together with the systems engineers and other design disciplines to make design decisions. In some cases, the human engineer will need to determine how to mitigate, eliminate, or compensate for environmental effects. As more of the system's physical design is completed, additional induced environmental factors, such as vibration and noise, will become apparent or better defined. The human engineer must therefore iteratively review or be continually involved in development of system designs to continue to identify induced factors and determine how external environmental factors may affect humans. In some cases, the human engineer will make assumptions about environmental factors that are present and will need to clarify or present those assumptions to the systems engineers. High levels of noise in a control center, for example, will impair verbal communications unless noise-attenuating communications headsets are used.

Once the effects of environmental factors have been assessed, it must be determined whether or not desired levels of system and human performance can be achieved. Any performance effects of the environment will need to be included in system or component models and simulations. The systems engineers and other designers will need to know about such performance degradations, and will also need to be given specific requirements for and performance impact of equipment to mitigate or inhibit

environmental effects that have been identified. Approaches to mitigate environmental effects include breathing or life support apparatuses, vibration damping, noise cancellation, hearing protection, protective clothing, lighting, and operator exposure or duty limits.

IEEE 1220-1998: *6.1.8 – Define utilization environments*
EIA-632: *Requirement 16 – System Technical Requirements*
Requirement 24 – Risk Analysis
SE/SW CMM: *Requirements Development, SP 3.5-1 – Validate Requirements*
Technical Solution, SP 1.2-2 – Evolve Operational Concepts and Scenarios
Product Integration, SP 1.2-2 – Establish the Product Integration Environment
Verification, SP 1.1-1 – Establish a Verification Strategy
Verification, SP 1.2-2 – Establish the Verification Environment
Validation, SP 1.1-1 – Establish a Validation Strategy
Validation, SP 1.2-2 – Establish the Validation Environment
DoD 5000.2-R: *C2.8.5.4 – Personnel Survivability and Habitability*
C2.8.5.5 – Human Factors Engineering
C2.8.6 – Environment, Safety, and Occupational Health (ESOH) Considerations
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
C5.2.3.5.9.2 – Habitability and Personnel Survivability
C5.2.3.5.10 – Environment, Safety, and Occupational Health (ESOH)
SE OSDs: *SE110 – Define and Assess Operational Environment*

3.2 REQUIREMENTS ANALYSIS

During requirements analysis, source requirements are identified, clarified, and prioritized. Requirements are assessed for consistency, coherence, and completeness. The requirements are broken down or decomposed into greater detail. Each lower-level requirement must be traceable to higher-level requirements. As the requirements are defined in greater detail, they will become more specific to the planned implementation of the system, and the involvement of designers within different disciplines becomes necessary. Examples of inputs and outputs of human engineering activities related to Requirements Analysis are listed in Table 3-5.

Human engineering involvement in requirements analysis activities is vital since human engineering-related criteria are unlikely to be assessed without the prior definition of appropriate requirements. Unfortunately, definition of requirements pertaining to the user population and human-system integration is at times deferred until later in the development process. Human engineering requirements may also be defined at an insufficient level of detail, stating, for example, that the system "shall be usable." Such vague requirements alone provide no guidance for design decisions, nor do they permit human engineering design evaluations to carry any weight in tradeoff decisions. Due to their tremendous impact on the overall system life cycle, requirements relating to both training and selection must also be addressed at this stage of the development process.

Defining training requirements enables the anticipated amount of training to be used as a factor in design tradeoffs.

Table 3-5. Human Engineering Inputs and Products in Requirements Analysis

Inputs	Products
• Source requirements • Explicit constraints • Requirements of comparison systems • Higher-level HCI style guide(s) • Human capabilities and limitations • System capabilities and limitations	• Anticipated knowledge, skills, and abilities (KSAs) of users • Decomposed requirements • Implicit constraints • Human performance requirements such as time allowed and accuracies • Human engineering design requirements • Hardware and software requirements to support operators and maintainers • Decision and Information Requirements • System-specific HCI style guide • Information Exchange Requirements (IERs)

Definition of human engineering requirements independent of system-wide requirements also degrades their ability to positively impact designs. Human performance requirements must be related to system-level or other engineering requirements in order to develop optimal designs. While it is certainly simpler to define and test human engineering requirements separately, the impact of human engineering requirements and design decisions on overall system performance needs to be addressed.

3.2.1 Human Engineering Constraints

Constraints are implied requirements that restrict the design of a system. They are imposed by external limitations and will impact specifications. Many more design constraints will be involved in the development of systems that retain major components of previous systems. If more constraints are known early in the design process, it is easier to narrow the design space for the system.

Constraints that impact the work of the systems engineer are likely to impact the work of the human engineer as well. To ensure that all participants are aware of the restrictions, overall constraints of the system should be documented. These should include constraints that come from inherent capabilities and limitations of humans. For example, basic human physiology limits the amount of g-force that a piloted aircraft can safely withstand, and the limits of working memory restrict the number of options that can be evaluated at one time. Additional constraints may arise due to design decisions or analyses by the human engineer. More specific constraints will arise in different user

populations due to the specific knowledge bases and skill sets available. Once the characteristics of the user population become more certain, more constraints may become apparent. As they arise, these constraints must be identified and passed on to other design disciplines. In some cases, constraints from different disciplines must be developed and documented in parallel, requiring collaboration between design disciplines.

IEEE 1220-1998: *6.1.2 – Define project and enterprise constraints*
6.1.3 – Define external constraints
6.1.15 – Define human factors

EIA-632: *Requirement 5 – Technical Effort Definition*
Requirement 14 – Acquirer Requirements
Requirement 15 – Other Stakeholder Requirements
Requirement 16 – System Technical Requirements
Requirement 19 – Specified Requirements

SE/SW CMM: *Requirements Management, SP 1.1-1 – Obtain an Understanding of Requirements*
Requirements Management, SP 1.2-1 – Obtain Commitment to Requirements
Requirements Development, SP 1.1-1 – Collect Stakeholder Needs
Requirements Development, SP 1.1-2 – Elicit Needs
Requirements Development, SP 1.2-1 – Transform Stakeholder Needs, Expectations, Constraints, and Interfaces into Customer Requirements
Requirements Development, SP 2.1-1 – Establish Product and Product Component Requirements
Requirements Development, SP 3.3-1 – Analyze Requirements
Requirements Development, SP 3.5-1 – Validate Requirements
Requirements Development, SP 3.5-2 – Validate Requirements with Comprehensive Methods
Technical Solution, SP 2.2-1 – Develop a Technical Data Package
Technical Solution, SP 2.2-3 – Establish a Complete Technical Data Package
Product Integration, SP 1.1-1 – Establish a Product Integration Strategy

DoD 5000.2-R: *C2.7.2 – Interoperability*
C2.8.5 – Human Systems Integration (HSI)
C4.4 – Affordability
C4.5.4 – Manpower
C5.2.3.1 – Requirements Analysis
C5.2.3.5.9 – Human Systems Integration (HSI)

SE OSDs: *SE130 – Identify Constraints and Analyze Operational Requirements*

3.2.2 Human Performance Requirements and Human Engineering Design Requirements

Much of the early work in developing a system involves the definition and decomposition of requirements. Requirements from a variety of sources and disciplines must be analyzed to remove conflicts. The human engineer is primarily responsible for two types of requirements, human performance requirements and human engineering design requirements. Human performance requirements include times and accuracies for tasks

assigned to humans. The human engineer must ensure that the proposed requirements are in fact achievable by the intended operators and users. The human engineer may in some cases define the human performance requirements based on external requirements, specifications of other system components, or the capabilities and limitations of the prospective operators and users. The human engineering design requirements concern specific aspects of the hardware and software that are necessary to fit the operators and assist them in their assigned tasks. These requirements define what must be designed and constructed to permit the operators and users to interact with one another and the rest of the system. Human engineering input is required to ensure the completeness of system requirements involving users or operators.

Human performance requirements are frequently derived from or at least bounded by other performance requirements levied on the system such as the time available to complete an action or to make a decision. The accuracy, response time, and other attributes of the operator tasks will affect the ability of the system to satisfy related requirements at the system level. Therefore, the human performance requirements should be in a format similar to that of the system-level requirements. Common format within a given project, both visually and electronically, will make the derivation of human performance requirements easier, and it will also make the verification or approval of those requirements by the systems engineers a simpler task. Other domains will also be more apt to incorporate requirements in a format similar to their own. In the same way, the human engineering design requirements should share a common format. In the case of these requirements, a common format is even more important as they must be reviewed or followed by system designers in other disciplines. Although the human engineer is the one who may set specifications for the design of other system components, the complete design and construction of those components will be the responsibility of others within the project. As designs become more detailed, a continuous interaction between the human engineer and other disciplines becomes more valuable. The implementation of the requirements needs to be verified, and additional design decisions need to be made as the design progresses.

IEEE 1220-1998: *6.1.11 – Define performance requirements*
6.1.14 – Define design characteristics

EIA-632: *Requirement 4 – Process Implementation Strategy*
Requirement 5 – Technical Effort Definition
Requirement 10 – Progress Against Requirements
Requirement 13 – Information Dissemination
Requirement 14 – Acquirer Requirements
Requirement 15 – Other Stakeholder Requirements
Requirement 16 – System Technical Requirements
Requirement 19 – Specified Requirements
Requirement 25 – Requirement Statements Validation
Requirement 26 – Acquirer Requirements Validation
Requirement 27 – Other Stakeholder Requirements Validation
Requirement 28 – System Technical Requirements Validation
Requirement 29 – Logical Solution Representations Validation

SE/SW CMM: *Requirements Management, SP 1.1-1 – Obtain an Understanding of Requirements*
Requirements Management, SP 1.2-1 – Obtain Commitment to Requirements
Requirements Development, SP 1.1-1 – Collect Stakeholder Needs
Requirements Development, SP 1.1-2 – Elicit Needs
Requirements Development, SP 1.2-1 – Transform Stakeholder Needs, Expectations, Constraints, and Interfaces into Customer Requirements
Requirements Development, SP 2.1-1 – Establish Product and Product Component Requirements
Requirements Development, SP 2.3-1 – Identify Interface Requirements
Requirements Development, SP 3.3-1 – Analyze Requirements
Requirements Development, SP 3.5-1 – Validate Requirements
Requirements Development, SP 3.5-2 – Validate Requirements with Comprehensive Methods
Technical Solution, SP 2.2-1 – Develop a Technical Data Package
Technical Solution, SP 2.2-3 – Establish a Complete Technical Data Package

DoD 5000.2-R: *C1.2 – Thresholds and Objectives*
C1.4 – Acquisition Program Baseline (APB)
C2.2 – Requirements
C2.8.5 – Human Systems Integration (HSI)
C2.8.6 – Environment, Safety, and Occupational Health (ESOH) Considerations
C5.2.3.1 – Requirements Analysis
C5.2.3.5.9 – Human Systems Integration (HSI)
C5.2.3.5.10 – Environment, Safety, and Occupational Health (ESOH)

SE OSDs: *SE130 – Identify Constraints and Analyze Operational Requirements*
SE140 – Identify Functional and Performance Requirements

3.3 FUNCTION ANALYSIS

Function analysis involves the translation or allocation of the system's requirements to a functional architecture that defines how the system will meet those requirements. The functional architecture does not include references to function allocation or implementation. Once a set of functions that satisfy the requirements has been identified, they are decomposed into greater levels of detail, and interaction between the functions is defined. Examples of inputs and products produced as part of or with the aid of human engineering activities in this stage are provided in Table 3-6.

Function analysis is more easily completed without consideration of human involvement in the system, but many of the products of function analysis are critical for later human engineering-related activities. Specific functions related to human involvement have to be identified, and information and decision requirements related to functions need to be defined so that they may be used as criteria in later function allocation decisions. A user's decision-making process, for example, needs to be well defined during function analysis whether the user is making that decision alone or with the aid of decision-support software.

Table 3-6. Human Engineering Inputs and Products in Function Analysis

Inputs	Products
• Mission analyses • Comparative system analyses • Activity analyses • Requirements analyses • Subject Matter Expert inputs	• Critical functions • Additional functions for user support • Functional architecture • Function flow diagrams • Decision-action diagrams • Information flow charts • Support requirements for users • Required design characteristics to support users

3.3.1 Functional Decomposition

A high-level set of desired system functions is typically specified very early in the development of a system and derived from a high-level requirements document like an Operational Requirements Document. These top-level functions must then be broken down into their component subfunctions that meet the system's requirements within the specified constraints. Once the functions have been defined and decomposed to the lowest level, they can be allocated to be performed by humans, hardware, software, or combinations. Until the functions can be decomposed to a detailed level, most allocations will be somewhere between "fully manual" and "fully automated." A single function can often be decomposed in a variety of ways. Choosing the best decomposition before function allocation decisions are made can reduce later design changes.

Decisions on function allocation are typically made iteratively as functional decomposition continues. Allocating the functions permits their parameters to be specified in greater detail and serves to verify the decomposition. Decomposition of the functions must continue since the attributes of the subfunctions are needed to support design decisions. Although the definition and decomposition of functions is independent of allocation and may be seen as not relevant to the human engineer, the results of the decomposition and analysis will be used in later design work. Much of the information that is critical to the human engineer may not be of interest to those performing the decomposition. Timing requirements, available information, required information, and other inputs may be necessary for subsequent human engineering design decisions. The optimal way to ensure that the necessary information is defined is to have the human engineer work in conjunction with other designers. This collaboration will allow the definition of function parameters required for the work of the human engineer. The alternative is to wait until the human engineer needs additional information and either request the necessary information or generate it at that point. Any new functional information that the human engineer independently generates will need to be reviewed and verified by other designers.

IEEE 1220-1998 *6.3.1 – Functional context analysis*
6.3.2 – Functional decomposition
EIA-632: *Requirement 17 – Logical Solution Representations*
SE/SW CMM: *Requirements Development, SP 3.2-1 – Establish a Definition of Required Functionality*
DoD 5000.2-R: *C5.2.3.2 – Functional Analysis/Allocation*
SE OSDs: *SE210 – Functional Definition*

3.3.2 Review of Functional Architecture

The functional architecture of a system represents, without specifying allocations, what a system needs to do to meet its requirements. The architecture includes the required functions, the flow and timing between functions, and their respective inputs and outputs. As with functional decomposition, the functional architecture is highly relevant to the human engineer despite the fact that it does not explicitly include any allocation decisions. The functional architecture does, however, depend upon some allocation decisions. Some functions are required in order to support specific implementation options. For example, a system with a nuclear power source will have a refueling function just as other implementations do, but the timing of the function is likely to be longer in both duration and periodicity. If humans are to be included as part of a system, functions such as life support, food supply, communications, supervision, and decision support are relevant and must therefore be reflected in the functional architecture.

It is the human engineer's responsibility to review the functional architecture and ensure that it includes all aspects relevant to the inclusion of humans in the system and their projected roles. In the case of top-level system requirements, the human engineer can provide feedback as to whether or not additional high-level functions need to be added to account for the role of humans proposed in the system concept. While it is likely that few if any functions are added at this level, additional functions may be catalogued for inclusion during functional decomposition. The functional flow of the system needs to be assessed to ensure that it is compatible with the inclusion of humans in the system. Enhanced analysis is possible as more allocation decisions are made and as greater levels of decomposition are reached. The functional architecture needs to be compared to the human engineering requirements, specifically human performance requirements, to determine whether or not those requirements can be satisfied by the functional architecture.

IEEE 1220-1998: *6.3.3 – Establish functional architecture*
6.4 – Functional verification
EIA-632: *Requirement 17 – Logical Solution Representations*
SE/SW CMM: *Requirements Development, SP 3.2-1 – Establish a Definition of Required Functionality*
Verification, SP 2.1-1 – Prepare for Peer Reviews
Verification, SP 2.2-1 – Conduct Peer Reviews
Verification, SP 2.3-2 – Analyze Peer Review Data

DoD 5000.2-R: *C2.8.5.4 – Personnel Survivability and Habitability*
C5.2.3.2 – Functional Analysis/Allocation
C5.2.3.5.9.2 – Habitability and Personnel Survivability
SE OSDs: *SE210 – Functional Definition*

3.4 FUNCTION ALLOCATION

The goal of function allocation is to effectively distribute the functions of the system between humans and technology. The functional elements are identified and then utilized in the creation of functional element allocation options. In developing these allocation options the systems engineer considers the project constraints, requirements, and the capabilities and limitations of both technology and the users, whether as individuals or as teams. The constraints and requirements to be considered are usually developed early in the overall process when the systems engineer is assessing all the constraints on the system and its operational requirements. The systems engineer determines the capabilities and limitations of the potential technologies, as well as the possible use of commercial off-the-shelf products, while information about operator capabilities and limitations will come from the human engineer. In addition, certain functions may be required to be allocated specifically to operators or technology. These allocations are made first, and then the remaining options are assessed and allocated. This mandatory function allocation, as well as the development of functional element allocation options, is an important step in the systems engineer's creation of implementation concepts or candidate physical architectures for the system. Samples of inputs and products of the collaboration of human engineering activities with other system development activities are shown in Table 3-7.

Table 3-7. Human Engineering Inputs and Products in Function Allocation

Inputs	Products
• Function allocation evaluation criteria • Mission analyses • Comparative system analyses, including knowledge, skills, and abilities (KSAs) of operators/maintainers • Activity analyses • Requirements analyses • Subject Matter Expert inputs • Function analyses (decision-action analyses, information flows, function flows) • Mandatory allocations • Technology and tradeoff studies, if available, for software and hardware • Concept of operations • Human roles	• Allocations of system functions to hardware, software, humans, or combinations • Support requirements for users • Required design characteristics to support users • Predictions of knowledge, skills, and abilities (KSAs) for user tasks • Predicted staffing and training needs • Operational sequence diagrams • Preliminary procedure requirements • Predicted workload • Technology & tradeoff studies of human-system interface technologies • System and function models

Since details of human capabilities and limitations are involved, much of the function allocation responsibility falls into the realm of human engineering. One way for the human engineer to go about this task is to identify the capabilities and limitations of both the potential operators and available technologies and then weigh the various options to determine possible allocations. The human engineer first determines which functions must be allocated specifically to a human or machine and then conducts the tradeoffs to develop additional potential allocations. Some allocation decisions may require the definition of new tasks for the user, such as the addition of supervisory and monitoring tasks for an automated function. The mandatory and additional allocation recommendations are preferably codeveloped by the human engineer and systems engineer, or developed independently by the human engineer. The systems engineer must then approve the recommendations.

The process of allocating functions between users, software, hardware, and combinations is a critical step in improving system performance. Unfortunately, the process is not well supported by design tools and is commonly performed in an ad hoc manner or even omitted as an explicit step in the development process. The allocation process has to be based on effective criteria or guidance such as a statement of intended human roles, not solely on user opinion or replication of implementations from previous systems. Description of intended roles of the humans within the system – whether they are to be primarily supervisors, monitors, or active participants – is critical to guiding allocation decisions and later software development.

Allocation decisions will need to include inputs from technology experts, but an understanding of how that technology impacts the users is also required. Allocations performed on a platform-by-platform or subsystem-by-subsystem basis need to address allocation to users or automation as part of that process.

3.4.1 Consideration of Human Engineering Technologies

In order to make the best decisions about which functions should be allocated to technology, it is important to be aware of the types of technology available and their inherent capabilities and limitations. The systems engineer conducts studies to assess the general capabilities and limitations of the technology available that may be useful for the particular system under design.

The human engineer may conduct additional research to identify technologies capable of supporting or replacing humans within the system and then analyze the capabilities of those technologies. Relevant technologies include decision support systems, human performance models, and human-computer interaction techniques. An accurate assessment of the potential human engineering technology allows the human engineer to trade off these factors with the capabilities and limitations of the operator. The human engineer's identification of the human engineering technologies and assessment of their capabilities and limitations should be done with the help of other disciplines to avoid duplication of work and ensure common assumptions.

The human engineer can eliminate redundant work by consulting with the systems engineer and making use of the previous systems engineering studies of technology capabilities and limitations. Additionally, the human engineer can aid the systems engineer by providing necessary data about the user population. The human engineer will consider the future users and assess their capabilities and limitations and anticipated training requirements. These capabilities and limitations will be important factors in the human engineer's function allocation but will also be needed by the systems engineer to assess the capabilities and limitations of the system as a whole.

IEEE 1220-1998: *6.5.5 – Assess technology requirements*
6.5.11 – Develop models and fabricate prototypes
EIA-632: *Requirement 5 – Technical Effort Definition*
Requirement 16 – System Technical Requirements
SE/SW CMM: *Requirements Development, SP 2.3-1 – Identify Interface Requirements*
Requirements Development, SP 3.4-3 – Evaluate Product Cost, Schedule, and Risk
Technical Solution, SP 1.1-2 – Develop Detailed Alternative Solutions and Selection Criteria
Technical Solution, SP 1.3-1 – Select Product Component Solutions
Technical Solution, SP 2.3-1 – Establish Interface Descriptions
Technical Solution, SP 2.3-4 – Perform Make, Buy, or Reuse Analyses
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C3.4 – Developmental Test and Evaluation (DT&E)
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
C7.5 – Technology Maturity
SE OSDs: *SE310 – Synthesize Multiple Physical Architectures*

3.4.2 Early Identification of Mandatory Allocations

One of the first steps in allocation is the identification of functions that must be allocated specifically to a human or a particular technology. For example, if there is a complicated numerical calculation that must be completed very quickly, this should probably be allocated to software components. On the other hand, if there is an important decision that must be made, such as whether or not to fire on a potential enemy, it may be determined that this function should not be left to a machine but should be the sole responsibility of an operator. The systems engineer will make these mandatory allocation decisions, based in part on recommendations from the human engineer.

There are a number of information sources that might be important for the human engineer to consider while developing mandatory allocation decisions. Information external to the design may include documents such as the Concept of Operations or human engineering literature applicable to the design domain. Sources of information from within the current project that might be useful include the system use scenarios and the variety of documents outlining requirements, constraints, and capabilities/limitations.

The systems engineer will work with the human engineer and provide him with a variety of information sources developed by the systems engineering team, including the list of functional elements, draft functional architectures, and cost constraints. The systems engineer and human engineer should also consider if there are additional technologies that are available or expected to be available that should be investigated for an optimal allocation. If so, systems engineering trade studies might be conducted to assess the options and the results of these studies would be shared with the human engineer.

The development and approval of the recommendations for the mandatory design allocation follows the general process for allocation recommendations (as outlined below). However, it is important to note that the human engineer should consider the mandatory allocations early in the design process and present this information to the systems engineer. If the mandatory allocation decisions are finalized early, this can prevent wasted effort on designs that do not match the mandatory requirements.

IEEE 1220-1998: *6.5.1 – Group and allocate functions*
EIA-632: *Requirement 17 – Logical Solution Representations*
Requirement 18 – Physical Solution Representations
SE/SW CMM: *Requirements Development, SP 2.2-1 – Allocate Product Component Requirements*
Technical Solution, SP 1.1-1 – Develop Alternative Solutions and Selection Criteria
Technical Solution, SP 1.1-2 – Develop Detailed Alternative Solutions and Selection Criteria
Technical Solution, SP 1.3-1 – Select Product Component Solutions
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C5.2.3.2 – Functional Analysis/Allocation
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
SE OSDs: *SE310 – Synthesize Multiple Physical Architectures*

3.4.3 Development and Approval of Function Allocation Recommendations

Both the mandatory function allocations and the additional allocations that follow must be developed by taking into account a number of factors and considering a variety of information from different sources. This can be a complicated step in the design where conflicting costs and benefits require careful tradeoffs. If the allocation decision is ambiguous, systems engineering trade studies or human engineering studies, such as user review or performance and workload estimation, may need to be performed to generate the information required to make the decision. The systems engineer, human engineer, and other designers will ideally generate the allocation recommendations jointly, but they may instead be developed independently by the human engineer and submitted to the systems engineer for approval. If the human engineer prepares the options, then the expectations of the systems engineer (i.e., number and variety of options desired) should be taken into account.

Once the recommendations are developed, they must be approved by the systems engineer. If the systems engineer was also involved in development, then the approval should be a simple step. However, if the human engineer developed the recommendations independently, the systems engineer may have feedback or suggestions for changes. In addition, the systems engineer should be aware of other influential decisions that might have been made or are being considered. Thus, the systems engineer should be able to take into account the objectives of the human engineer's suggested allocation and the objectives of the activities of other disciplines. This may be an iterative process of refinement until the systems engineer and human engineer can agree on a set of allocations.

IEEE 1220-1998: *6.5.1 – Group and allocate functions*
EIA-632: *Requirement 17 – Logical Solution Representations*
Requirement 18 – Physical Solution Representations
SE/SW CMM: *Requirements Development, SP 2.2-1 – Allocate Product Component Requirements*
Technical Solution, SP 1.1-1 – Develop Alternative Solutions and Selection Criteria
Technical Solution, SP 1.1-2 – Develop Detailed Alternative Solutions and Selection Criteria
Technical Solution, SP 1.3-1 – Select Product Component Solutions
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C5.2.3.2 – Functional Analysis/Allocation
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
SE OSDs: *SE310 – Synthesize Multiple Physical Architectures*

3.5 TASK DESIGN AND ANALYSIS

Once the functions of a system have been assigned to particular system components, the functions can typically be defined to greater resolution of detail. What was a generalized function must be expanded to describe exactly how the specified system components will accomplish the functions. The allocation of a function to a human creates or defines what is typically referred to as a task. Given the constraints of the system's requirements and functional architecture, the human engineer needs to define precisely how the humans within the system will carry out their assigned tasks. The human tasks include both tasks that humans do alone and tasks that involve their interaction with other parts of the system. The order and interactions of the tasks can be defined and modeled to verify that they meet the system requirements. Examples of both inputs to and products of Task Design and Analysis are listed in Table 3-8.

Without an explicit effort in task design, user tasks in an implemented system will not conform to user needs and activities. Systems commonly end up with user interfaces that arrange information on the basis of information sources instead of task order, frequency of use, or other attributes of the task. Even minor interface manipulation tasks – such as an extra mouse click to access or close a data window – can have a significant impact on

Table 3-8. Human Engineering Inputs and Products in Task Design and Analysis

Inputs	Products
• Mission analyses • Comparative system analyses, including knowledge, skills, and abilities (KSAs) of users • Activity analyses • Requirements analyses • Subject Matter Expert inputs • Function analyses (decision-action analyses, information flows, function flows) • Allocations of system functions to hardware, software, humans or combinations • Technology and tradeoff studies, if available, for software, hardware, and human engineering technologies • Functional element allocation options • Physical architecture • System and function models	• Task list • Task interactions and sequences • Task models • Timeline analyses • Support requirements for users • Required design characteristics to support users • Simulations and prototypes • Predictions of knowledge, skills, and abilities (KSAs) for user tasks • Predicted staffing and training needs • Preliminary procedure requirements • Preliminary predictions of cognitive and physical workload • Preliminary predictions of human and system performance

human and system performance if they occur frequently. Both the frequency and duration of human tasks need to be estimated to adequately evaluate designs.

3.5.1 <u>Development of the Task List</u>

Before the analysis of the tasks of the humans, it is necessary to compile a complete list of the tasks to be considered. This process may also include the decomposition of tasks, if such decomposition would be useful. Most likely, the human engineer will be responsible for creating the task list; however, he or she may want to work with the systems engineer and engineers in other domains to achieve a better understanding of the tasks. Systems engineering documents, such as the functional element allocation options and the physical architecture, may be of great use to the human engineer by providing a context for the tasks. The systems engineer might also provide additional, amplifying information, such as decisions by other disciplines that influence the tasks of the humans.

The human engineer will assess the information from the systems engineer and other design engineers and devise a complete list of human tasks. Both physical and cognitive tasks will have to be considered, and a wide variety of methodologies can be employed to do so. Additional inputs to the development of the task list include the approved function

allocations and interface-specific tasks, if applicable. Interface-specific tasks are those that are created as a function of the interface that is chosen, and are based on the interface concepts and designs. Interface-specific tasks are normally defined following task design; however, due to the iterative nature of the design process, the human engineer may redevelop the task list in light of later decisions.

IEEE 1220-1998: *6.5.2 – Identify design solution alternatives*
EIA-632: *Requirement 17 – Logical Solution Representations*
Requirement 18 – Physical Solution Representations
SE/SW CMM: *Technical Solution, SP 1.1-2 – Develop Detailed Alternative Solutions and Selection Criteria*
Technical Solution, SP 1.2-2 – Evolve Operational Concepts and Scenarios
Technical Solution, SP 2.2-3 – Establish a Complete Technical Data Package
DoD 5000.2-R: *C5.2.3.5.9.1 – Human Factors Engineering (HFE)*
SE OSDs: *SE320 – Evaluate and Select Preferred Architecture*

3.5.2 Identification of Task Characteristics, Interactions, and Sequences

Once the task list has been generated, the particular characteristics of each task must be outlined. This further definition facilitates a better understanding of the individual tasks and can be used in other steps of the task design and analysis process, such as task allocation and definition of required skills and abilities. In order to attain a full understanding of the tasks, the interactions between the tasks or the possible sequences in which they will be accomplished should also be identified. The identification of interactions and sequences among tasks is important both to better characterize the tasks themselves and also to create accurate task models.

The task design and analysis portion of the human engineering process might be highly iterative, and the results of both these identifications can act as inputs for each other. Additional information sources might include the human engineer's task list and the externally set operational requirements. Systems engineering contributions include the functional element allocation options and general systems engineering guidance on the current system design. This systems engineering advice is imperative in order to accurately identify interactions with nonhuman elements of the system. These task interactions include interactions between humans and automated functions and/or other system components. The need for users to monitor or supervise automated systems must be addressed.

There is also an interaction between the human engineer and systems engineer because the human engineer's task definition is dependent on the system design, since this design will impact the possible ways to accomplish the tasks. The human engineer can create the most useful set of task characteristics only by checking with the systems engineer to verify that the human engineer has a correct understanding of the system design. The most accurate representation of the system design is probably embodied in the systems engineer's current candidate physical architectures. The systems engineer's functional decomposition will also be useful to consider. If the decomposition is not to the level of

detail required by the human engineer, a further functional analysis may be necessary. Other useful sources for determining if all tasks have been identified are task listings from comparable systems. These may not be applicable to the system under design, but they can help provide cues for finding missing tasks.

IEEE 1220-1998: *6.5.2 – Identify design solution alternatives*
EIA-632: *Requirement 17 – Logical Solution Representations*
Requirement 18 – Physical Solution Representations
Technical Solution, SP 1.2-2 – Evolve Operational Concepts and Scenarios
Technical Solution, SP 2.2-3 – Establish a Complete Technical Data Package
DoD 5000.2-R: *C5.2.3.5.9.1 – Human Factors Engineering (HFE)*
SE OSDs: *SE320 – Evaluate and Select Preferred Architecture*

3.5.3 Selection of Modeling Tools and Techniques

Modeling techniques are typically used to evaluate or compare candidate designs. Models can be constructed at the functional level or in the context of the system's implementation. Creating models of external systems can help to define functional and performance requirements for the system under development. The utility of modeling techniques and executable models (i.e., models that can run, or execute, in a simulated environment) in particular can be significantly increased if models used by different designers are interoperable. Systems engineers can then create higher-level models of the system by combining models developed for different subsystems or within different disciplines.

An important step for the human engineer in task design and analysis is to select appropriate task-level tools and techniques that will result in a useful and appropriate model. The tools and techniques should be chosen early enough to ensure that they can support the inclusion of relevant information from the task analysis. These modeling tools and techniques will determine how the task list, task characteristics, and task interactions and sequences will be used to create task models. Comments from subject matter experts might also be useful in tailoring and validating task models. In order to have task models that are compatible with system-level models and models from other design disciplines, the human engineer and systems engineer must agree on the modeling tools to be utilized. The human engineer should also request the systems engineer's input on the models, since they will include nonhuman elements. Since model development can take considerable time and resources, communication between the systems engineer and human engineer is important to ensure that the models selected can be used across design disciplines. Given the importance of resource allocation to support system and subsystem modeling, overall project plans should include human engineering modeling as a program milestone.

IEEE 1220-1998: *6.5.2 – Identify design solution alternatives*
6.5.11 – Develop models and fabricate prototypes
EIA-632: *Requirement 5 – Technical Effort Definition*
Requirement 13 – Information Dissemination

Requirement 23 – Tradeoff Analysis
SE/SW CMM: Technical Solution, SP 2.1-1 – Use Effective Design Methods
Verification, SP 1.1-1 – Establish a Verification Strategy
Validation, SP 1.1-1 – Establish a Validation Strategy
DoD 5000.2-R: C5.2.3.5.2.3 – Planning the M&S Approach
C5.2.3.5.2.4 – M&S Standards
SE OSDs: SE320 – Evaluate and Select Preferred Architecture
SE330 – Integrate System Physical Configuration

3.5.4 Task and Function Audit

In synthesizing the physical architecture, allocations between humans and machines will be reflected in the design of interfaces. The designers will have to verify that all functions in the functional architecture can be traced to human tasks or automated activities. A review of the task list – including interface- and team-specific tasks – should therefore find all of the tasks drawn from the function allocation in the interface and team concepts and designs. This review may be thought of as an audit of the interfaces with a mandatory consideration of all of the tasks from the analyses and simulations.

A confirmation of automation assumptions by the systems engineer and other designers is necessary to ensure that the job and task design performed by the human engineer does not omit necessary functions. The human engineer may need to give feedback to the systems engineer about tasks that could be automated or tasks that need further design support. For example, further function analysis may be required, an operator may need additional information to support decision-making, or additional automation or system functionality may improve system performance.

IEEE 1220-1998: 6.5.7 – Define physical interfaces
6.5.15 – Final design
EIA-632: Requirement 17 – Logical Solution Representations
Requirement 18 – Physical Solution Representations
SE/SW CMM: Technical Solution, SP 2.1-1 – Use Effective Design Methods
Verification, SP 1.2-2 – Establish the Verification Environment
Verification, SP 2.1-1 – Prepare for Peer Reviews
Verification, SP 2.2-1 – Conduct Peer Reviews
Verification, SP 2.3-2 – Analyze Peer Review Data
Verification, SP 3.1-1 – Perform Verification
DoD 5000.2-R: C5.2 – Systems Engineering
SE OSDs: SE320 – Evaluate and Select Preferred Architecture

3.6 HUMAN INTERFACE AND TEAM DEVELOPMENT

Designs and concepts for the interfaces between humans and software, hardware, and other humans need to be identified and developed. These interfaces can be considered at three different levels:

1. *Individual interfaces that represent a particular interaction based on the task analysis as well as performance and design requirements,*
2. *Combinations of interfaces for a design at the individual operator level based on the combination of tasks into roles, and*
3. *Interface designs and concepts for multiple operators based on the combination of individuals into crews or teams.*

The creation of the separate levels of interfaces may be performed in any order depending on the availability of resources and the priority of individual user versus crew/team development. Examples of some of the inputs and products related to these human engineering activities are shown in Table 3-9.

Table 3-9. Human Engineering Inputs and Products in Human Interface and Team Development

Inputs	Products
• Operational sequence diagrams	• User interface concepts and designs
• Information and decision requirements	• Crew and team concepts and designs
• Subject Matter Expert inputs	• User interface manipulation tasks
	• Team coordination tasks
	• Link analyses
	• Simulations and prototypes
	• Final system-specific HCI style guide

User interfaces, unfortunately, are often designed at the component or subsystem level instead of the user level. The entire combination of subsystems with which a given user interacts needs to be designed as a whole. Similarly, roles of individual users should be based on more than assigning each user to a particular piece of equipment. The roles of individual users within a team need to be explicitly designed instead of only being a function of how capabilities have been divided between pieces of equipment. Finally, user interfaces and team designs cannot be sufficiently evaluated without user involvement and human performance testing, and evaluation should occur while time and resources remain to make design changes.

3.6.1 Points of Human Interface

Points of human interface may be thought of as the content and the location (origin and destination) of information that may be conveyed between system components (specifically, between humans or between a human and a machine). Also included are the data to be transmitted, the nodes or elements between which the data is to be transmitted, when the data is transmitted and other interface-specific constraints, such as special conditions based on times and events. These points will be used in the development of the interface concepts and designs and will lead to interfaces at the individual level followed by the crew/team level.

The human engineer must identify all of the data to be transmitted and the location, or nodes, to and from which it will be transmitted. This is based on the functional decomposition and allocation, as well as the task analysis (which includes characteristics of tasks and the interactions and sequences), and any available internal and external interface information developed to that point by the systems engineer. These system-level interfaces must be decomposed for application to the level of automation.

The systems engineer helps verify allocation assumptions made by the human engineer and document the flow of information between humans and automation as well as identify additional points in the allocated functional architecture at which information or material is passed between humans and other system components. The role of the human engineer is to keep the points of interface in line with the initial system-level interfaces defined earlier in the systems engineering process and in line with the mission goals and constraints. Some interactions may be identified to address special needs or preferences of the users, such as creation and retrieval of user profiles or display configurations.

IEEE 1220-1998: *6.1.7 – Define interfaces*
6.3.1.2 – Define functional interfaces
6.5.7 – Define physical interfaces
EIA-632: *Requirement 18 – Physical Solution Representations*
SE/SW CMM: *Requirements Development, SP 2.3-1 – Identify Interface Requirements*
Technical Solution, SP 2.3-1 – Establish Interface Descriptions
Technical Solution, SP 2.3-3 – Design Comprehensive Interface
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C5.2 – Systems Engineering
C5.2.3.5.5 – Open Systems Design
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
SE OSDs: *SE210 – Functional Definition*
SE320 – Evaluate and Select Preferred Architecture

3.6.2 Selection of Human Interface and Team Guidelines

For the development of interfaces and teams, human engineers need to be aware of any existing guidelines applicable to the information or material passed between humans or between humans and equipment. The guidelines will also assist in keeping the design in accordance with constraints, heuristics and prior research of the particular engineering or design community. Guideline topics may include, but are not limited to, short term and working memory limitations, display and control modalities, physical or strength limitations, and group dynamics. These guidelines may also include those defined in, derived from, or implied by human and job/task requirements and organizational design.

Collaboration between the systems engineer and human engineer on the selection and implementation of standards and guidelines will help identify how system-level guidelines may be applicable to human engineering designs. Full application of system-level guidelines will often require the implementation of specific, lower level, detailed guidelines. For example, if a particular computer system architecture is selected, then

any associated user interface design guidelines should be implemented. Collaboration will also help identify how guidelines from one design discipline will impact other disciplines. The human engineer will identify additional useful guidelines, each of which may impact one or more other design disciplines.

IEEE 1220-1998: *6.1.3 – Define external constraints*
6.3.2.4 – Define data and control flows
EIA-632: *Requirement 18 – Physical Solution Representations*
SE/SW CMM: *Requirements Development, SP 2.1-1 – Establish Product and Product Component Requirements*
Technical Solution, SP 2.1-1 – Use Effective Design Methods
Technical Solution, SP 3.1-1 – Implement the Design
Verification, SP 1.1-1 – Establish a Verification Strategy
Validation, SP 1.1-1 – Establish a Validation Strategy
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C5.2.3.5.5 – Open Systems Design
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
SE OSDs: *SE130 – Identify Constraints and Analyze Operational Requirements*

3.6.3 Development of Interface and Team Concepts or Designs

Once an initial physical architecture has been synthesized and approved by the systems engineer, the interfaces between system components – such as humans, hardware, and software – can be developed. The interaction of humans with other system components will be based on the functional architecture, allocation decisions, and human engineering inputs. Some elements of interfaces both internal and external to the system will have already been defined as interfaces between functions within the functional architecture.

The human engineer will be responsible for designing and optimizing how individual humans interact with nonhuman system components and how humans act together as teams. Interface concepts and designs are developed based on requirements for interaction between humans and other system components specified earlier. Requirements such as the transfer of information, timing, need for minimizing communication, and physical location must all be satisfied by the interface designs. Due to the potentially significant and varied amount of information to be transferred, the process of developing team and individual interface concepts and designs is highly creative. The concepts are less detailed and concrete than the designs but are highly iterative with their development, as they feed off of each other. The development of interfaces includes their physical appearances and procedures for use. Interface guidelines and standards will influence the design of the interfaces. Interfaces must be considered collectively, in combinations, in order to minimize conflicts between different interfaces encountered by a single operator or user. Team designs will be based on the allocation of tasks and other responsibilities to different operators or team members, and will be influenced by such factors as individual workload and performance levels, team design principles, and overall performance requirements.

Team and individual interface design will be highly constrained due to other design decisions, such as specific pieces or types of hardware and software that are to be used. The human engineer attempts to develop team and interface designs that provide for optimal system performance within those constraints. The human engineer requires input from the systems engineer on system-level constraints (particularly those imposed by other design decisions), project and enterprise constraints, off-the-shelf availability, make-or-buy alternatives, state-of-the-art capabilities, design solution alternatives, etc. In some cases, constraints and design decisions that have been made previously may need to be reevaluated based on analysis of human performance within those constraints as well as interaction with other design disciplines to ensure the feasibility of the proposed designs.

IEEE 1220-1998: *6.1.2 – Define project and enterprise constraints*
6.1.3 – Define external constraints
6.1.7 – Define interfaces
6.3.2.4 – Define data and control flows
6.5.7 – Define physical interfaces
EIA-632: *Requirement 18 – Physical Solution Representations*
SE/SW CMM: *Technical Solution, SP 1.1-1 – Develop Alternative Solutions and Selection Criteria*
Technical Solution, SP 1.1-2 – Develop Detailed Alternative Solutions and Selection Criteria
Technical Solution, SP 2.2-1 – Develop a Technical Data Package
Technical Solution, SP 2.2-3 – Establish a Complete Technical Data Package
Technical Solution, SP 2.3-1 – Establish Interface Descriptions
Technical Solution, SP 2.3-3 – Design Comprehensive Interface
Product Integration, SP 2.1-1 – Review Interface Descriptions for Completeness
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C5.2.3.3 – Design Synthesis and Verification
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
SE OSDs: *SE130 – Identify Constraints and Analyze Operational Requirements*

3.7 PERFORMANCE, WORKLOAD, AND TRAINING LEVEL ESTIMATION

The systems engineer must evaluate the design or design options proposed by system designers within the different disciplines. Evaluation of a single option is necessary to determine whether or not the system requirements are satisfied, and multiple options may be evaluated in order to make a selection. The systems engineer may determine which options meet requirements and then select the best alternative, or the best option may be selected and then compared to the requirements. Overall system performance is an important parameter, but it typically consists of multiple variables that may be measured within different design disciplines. The design evaluations provided by different disciplines will all need to be available to the systems engineer to enable the tradeoff of different design options. Examples of the inputs to and products of these human engineering activities are listed in Table 3-10.

Table 3-10. Human Engineering Inputs and Products in Performance, Workload, and Training Level Estimation

Inputs	Products
• Operational sequence diagrams • Simulations and prototypes • Predicted user knowledge, skills, and abilities (KSAs) • User interface concepts and designs • Crew or team concepts and designs • Task models	• Required user knowledge, skills, and abilities (KSAs) • Training requirements • User/personnel selection requirements • Predicted cognitive and physical workload • Predicted human and system performance • Human performance and workload models

To help in the evaluation of concepts and designs, the human engineer will estimate the physical and cognitive workload levels of individuals and teams within the system. Workload stressors and their effects on human performance and operator coping strategies, as well as the effects of task neglect or delay, need to be defined in a way that allows their impact on system performance to be assessed. Workload and the resultant manning and training requirements are to be optimized to meet required performance levels.

User performance and workload can be difficult to estimate, but estimating them in isolation is not sufficient. The impact of workload on performance should be evaluated, and human performance predictions should be linked to system performance. Identifying how human performance impacts system performance enables human performance data and user interface features to be part of system-level tradeoff analyses. With respect to training, training requirements need to be assessed early in order for them to become a factor in design decisions.

3.7.1 Individual and Team Workload and Performance Estimation

Workload levels can significantly influence the performance of many system components or subsystems, including humans. Once workload levels are predicted, performance measures can be adjusted to determine the impact of workload. Given the tasks allocated to humans, the human engineer needs to estimate the cognitive and physical workload demands of the tasks on the operators and users. Executable models or simulations are typically used, but subjective feedback from test users or subject matter experts may also be employed. Workload levels must be estimated for different scenarios or situations, and changes in workload level can be as important as the absolute levels of workload. The scenarios must provide the conditions to elicit realistic workload. For example, if sustained operations over long periods are required, then the scenario should allow for it, or if there is a reasonable chance that many conditions could occur at the same time, then those conditions should be included. Workload on the team as a whole, frequently quantified as the time required to complete all assigned tasks, also needs to be estimated.

In order to be accurate, workload models need to include any operator or user tasks that are required to manipulate or utilize the human-machine interface.

To effectively estimate workload and performance, the human engineer needs up-to-date design data from the systems engineer and other designers. In order to create accurate models of how the humans interact with the rest of the system, the human engineer will need access to models of other system components. Without an accurate simulation of hardware and software functions and performance, the model of the human interactions will not be accurate. Information on other system components may be included as part of an executable model, or it may be used to create a physical prototype of portions of the system with which test users can interact. The true relevance of workload lies in its impact on human and system performance, not as a stand-alone measure, so workload measures should be easily integrated with performance models. Similarly, models of human performance need to be compatible with models that can predict overall system performance. The goal of the human engineer should not be to optimize human performance alone but to put human performance within acceptable levels to optimize overall system performance. This goal cannot be accomplished without human workload and performance models that are compatible with higher-level system models. Model compatibility will also be important when design changes are made that necessitate alterations to the models.

IEEE 1220-1998: *6.5.11 – Develop models and fabricate prototypes*
6.5.15 – Final design
EIA-632: *Requirement 10 – Progress Against Requirements*
Requirement 23 – Tradeoff Analysis
Technical Solution, SP 1.2-2 – Evolve Operational Concepts and Scenarios
Technical Solution, SP 1.3-1 – Select Product Component Solutions
Technical Solution, SP 2.1-1 – Use Effective Design Methods
Technical Solution, SP 2.3-3 – Design Comprehensive Interface
Product Integration, SP 3.3-1 – Checkout Assembled Product Components
Verification, SP 1.1-1 – Establish a Verification Strategy
Verification, SP 1.2-2 – Establish the Verification Environment
Verification, SP 1.3-3 – Establish Detailed Verification Plans
Verification, SP 3.1-1 – Perform Verification
Verification, SP 3.2-2 – Analyze Verification Results and Identify Corrective Action
Verification, SP 3.3-1 – Perform Reverification
Validation, SP 1.1-1 – Establish a Validation Strategy
Validation, SP 1.2-2 – Establish the Validation Environment
Validation, SP 1.3-3 – Define Detailed Validation Procedures
Validation, SP 2.1-1 – Perform Validation
Validation, SP 2.2-1 – Capture and Analyze Validation Results
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C5.2.3.3 – Design Synthesis and Verification
C5.2.3.5.2 – Modeling and Simulation (M&S)
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
C5.2.3.5.9.3 – Manpower Initiatives
SE OSDs: *SE320 – Evaluate and Select Preferred Architecture*

3.7.2 Training Concept Evaluation

The resources required to field and maintain a system are typically key concerns of the systems engineer. The overall cost of the system includes the cost to prepare it for use and to maintain it over its life cycle. If the human is considered to be part of the system, then the selection and training resources required to prepare and provide operators and users are just as relevant as the manufacturing resources required to provide hardware and software. The users and operators are frequently the most often changed and varied parts of the system. The training required to prepare them for use of the system and to maintain their qualifications as users and operators are important parts of the system life cycle support requirements.

In the development of a particular system, training may or may not be considered to be part of the human engineer's responsibilities. Even if the human engineer is not directly responsible for developing training requirements or training plans and methodologies, the work of the human engineer has direct and significant impact on these issues. The difference between the knowledge, skills, and abilities required to be a system user and operator and the knowledge, skills, and abilities possessed by prospective users and operators will determine the training and selection requirements. As the designer of all parts of the system with which the human operators and users interact, the human engineer has a direct influence on the training requirements. Additionally, human interfaces can be designed to provide for either ease-of-use or ease-of-learning. It is rare to be able to maximize both of these qualities, and their relative importance will influence the design of tasks, interfaces, and teams, all of which will in turn influence required training.

As the human tasks and interfaces are developed, the human engineer must be aware of constraints on training and selection. The knowledge, skills, and abilities expected to be available in prospective users and operators must be agreed upon by the human engineer and systems engineer. Requirements and constraints for the life cycle support of the system must be available to the human engineer to ensure that the training and selection requirements are compatible. Requirements such as those for on-the-job training or embedded training must be stated early to reduce the likelihood of design changes to meet these requirements at a later date. As training requirements are identified and a training concept emerges, it is very important to consider the overall training burden on the operators and users. Training for a particular interface feature, for example, may seem minimal, but when all such requirements are added up for that individual, the overall training load can be quite high. Training requirements can only be eliminated at the design stage – design problems eventually manifest themselves as training problems. From a life cycle perspective, the additional cost in the design stage may be outweighed by the recurring cost of continually training new users.

IEEE 1220-1998: *6.1.2 – Define project and enterprise constraints*
6.1.3 – Define external constraints
6.1.9 – Define life cycle process concepts
6.5.4 – Assess life cycle quality factors

EIA-632: *Requirement 21 – Transition to Use*

SE/SW CMM: *Requirements Development, SP 1.1-1 – Collect Stakeholder Needs*
Requirements Development, SP 1.1-2 – Elicit Needs
Requirements Development, SP 1.2-1 – Transform Stakeholder Needs, Expectations, Constraints, and Interfaces into Customer Requirements
Requirements Development, SP 3.1-1 – Establish Operational Concepts and Scenarios
Requirements Development, SP 3.4-3 – Evaluate Product Cost, Schedule, and Risk
Technical Solution, SP 1.2-2 – Evolve Operational Concepts and Scenarios
Technical Solution, SP 2.3-4 – Perform Make, Buy, or Reuse Analyses
Technical Solution, SP 3.2-1 – Establish Product Support Documentation
Product Integration, SP 1.1-1 – Establish a Product Integration Strategy
Product Integration, SP 1.2-2 – Establish the Product Integration Environment
Product Integration, SP 1.3-3 – Define Detailed Product Integration Procedures
Product Integration, SP 3.3-1 – Checkout Assembled Product Components

DoD 5000.2-R: *C2.8.5.2 – Personnel*
C2.8.5.3 – Training
C2.8.5.5 – Human Factors Engineering
C5.2.3.3 – Design Synthesis and Verification
C5.2.3.5.4.4 – Support Resources
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
C5.2.3.5.9.4 – Personnel Initiatives
C5.2.3.5.9.5 – Training

SE OSDs: *SE130 – Identify Constraints and Analyze Operational Requirements*

3.7.3 Tradeoff of Concepts and Designs

Once estimates of subsystem or component performance are available, different design alternatives can be traded off to determine the best available option. If multiple alternatives meet the system's functional and performance requirements, then those alternatives should be compared to select the optimal design. Typically, different options will have different strengths and weaknesses, so choosing an option that is strong in one area may decrease performance in other areas. For this reason it is important to have already determined the relative importance of the different design criteria to be used. A common understanding and application of the design criteria will permit better integration of the results of human engineering analyses. Even if a formal trade study approach is not employed, the definition of the design criteria will help to justify the selections and make it easier to deal with subsequent changes to system design.

Performing tradeoffs at the component level is typically a simpler task than doing so at higher levels of system design. The interactions between components and subsystems can increase drastically as higher-level designs are considered. Trade studies are typically easier to perform for designers who are only responsible for a single subsystem or feature of the system. The same group of people may have performed all of the design work, and as a result common models and metrics are often used. Due to different

models, techniques, and criteria used within different disciplines, trade studies can be more difficult for the systems engineer to perform. The systems engineer has to integrate the different models, data, and criteria that have been employed by the different disciplines or design teams.

In some cases, a tradeoff may involve the decision of whether or not to redesign portions of the system or the degree of redesign required. In such situations, the availability of resources such as time, money, and personnel become as important as technical feasibility. The systems engineers and designers within different disciplines, such as human engineering, must operate from the same set of resource assumptions in making these decisions. In proposing a design change, the human engineer should not simply state that there is a problem with the current design, but a potential alternative to the current design should also be provided. This alternative should be in line with the available resources and the selected design criteria for the project as a whole. Simply because the human engineer has the time and resources to recommend a design change does not mean that the other designers required to implement the change have the available resources. The human engineering feedback must be adequately prioritized in order for it to be useful.

IEEE 1220-1998: *6.7 – Systems analysis*
6.7.5 – Define trade-study scope
EIA-632: *Requirement 18 – Physical Solution Representations*
Requirement 23 – Tradeoff Analysis
SE/SW CMM: *Technical Solution, SP 1.3-1 – Select Product Component Solutions*
Technical Solution, SP 2.2-1 – Develop a Technical Data Package
Technical Solution, SP 2.2-3 – Establish a Complete Technical Data Package
Verification, SP 2.1-1 – Prepare for Peer Reviews
Verification, SP 2.2-1 – Conduct Peer Reviews
Verification, SP 2.3-2 – Analyze Peer Review Data
Verification, SP 3.2-2 – Analyze Verification Results and Identify Corrective Action
DoD 5000.2-R: *C1.3.3 – Cost/Schedule/Performance Tradeoffs*
C3.4 – Developmental Test and Evaluation (DT&E)
C4.2 – Analysis of Multiple Concepts
C5.2.3.4 – System Analysis and Control
SE OSDs: *SE320 – Evaluate and Select Preferred Architecture*

3.8 USER AND REQUIREMENTS REVIEW

Throughout the system development process, the system design must be reviewed with respect to both its requirements and the operational need. The system design must be compared to all requirements, not simply the top-level system requirements. Designers or verifiers within individual design disciplines must carry out some of this verification process. The conformance or nonconformance of the system design to its requirements must be reported to the systems engineer, who will determine the appropriate course of

action based on variables such as system performance and available resources. Sample inputs and products related to User and Requirements Review are shown in Table 3-11.

Table 3-11. Human Engineering Inputs and Products in User and Requirements Reviews

Inputs	Products
• Simulations and prototypes	• Heuristic usability evaluation results
• User interface concepts and designs	• Usability testing analyses
• Crew or team concepts and designs	• Human performance testing results
• Concept of operations	• Human performance and workload estimates for individual tasks
• Mission analyses	• Concept and system use scenario feedback
• Scenarios	• User interface feedback
• Human roles	• Crew/team feedback

User involvement is critical in producing effective and usable systems, and the type of involvement is important as well. Subjective feedback from users and subject matter experts is appropriate early in the development process, but it must be augmented with objective performance measures as designs become more specific. User review needs to happen early, not only after "all the bugs have been worked out of the software." Too much of a delay in user review reduces the possibility of being able to impact the design. Rapid prototyping of user interfaces should be employed, and reviews should not be restricted to a narrow sample of the expected user population. Finally, user review and human performance testing will be inconsequential if appropriate requirements for testing and evaluation were not previously specified.

3.8.1 Comparison to Human Engineering Requirements

As system designs are generated from requirements, those designs must then be verified to ensure that the requirements are satisfied. This verification is likely to be at least partially included in the responsibilities of designers in different disciplines. The originators of the requirements, the individuals who created the design, and the design verifiers may be the same people or each may be different.

It is highly probable that the human engineer will need to assess and ensure that designs generated by others satisfy human engineering requirements. The specific human engineering requirements, such as design requirements and human performance requirements, must be used to evaluate the designs. This evaluation must take place early enough to impact the designs, not only once the physical prototypes have been built. For a typical system, a large amount of the verification process may be spent on task or job designs or equipment design specific to human engineering. Other designs, however, will have to be reviewed for compatibility with human engineering requirements.

Verification may be performed through a variety of different means, ranging from inspection to modeling and simulation to user-in-the-loop testing.

IEEE 1220-1998: *6.6.2 – Conduct verification evaluation*
EIA-632: *Requirement 19 – Specified Requirements*
Requirement 20 – Implementation
Requirement 29 – Logical Solution Representations Validation
Requirement 30 – Design Solution Verification
Requirement 31 – End Product Verification
SE/SW CMM: *Technical Solution, SP 1.3-1 – Select Product Component Solutions*
Verification, SP 1.1-1 – Establish a Verification Strategy
Verification, SP 1.2-2 – Establish the Verification Environment
Verification, SP 1.3-3 – Establish Detailed Verification Plans
Verification, SP 3.1-1 – Perform Verification
Verification, SP 3.2-2 – Analyze Verification Results and Identify Corrective Action
Verification, SP 3.3-1 – Perform Reverification
Validation, SP 1.1-1 – Establish a Validation Strategy
Validation, SP 1.2-2 – Establish the Validation Environment
Validation, SP 1.3-3 – Define Detailed Validation Procedures
Validation, SP 2.1-1 – Perform Validation
Validation, SP 2.2-1 – Capture and Analyze Validation Results
DoD 5000.2-R: *C2.8.5 – Human Systems Integration (HSI)*
C2.8.6 – Environment, Safety, and Occupational Health (ESOH) Considerations
C5.2.3.3 – Design Synthesis and Verification
C5.2.3.5.9 – Human Systems Integration (HSI)
C5.2.3.5.10 – Environment, Safety, and Occupational Health (ESOH)
SE OSDs: *SE310 – Synthesize Multiple Physical Architectures*

3.8.2 User Review

Verification that the design of a system conforms to requirements is important, but the system design must also be validated. Precise conformance to written requirements does not always provide assurance that the system will conform to the needs of the users, operators, or purchasers. Reviewing potential designs with intended users and operators through means such as storyboards, simulations, and mockups can provide early and rapid validation feedback. Feedback from representative users on design iterations should be sought continually, and final evaluation of the design must include performance testing with appropriate users. Without such analyses, full validation that the system meets the operational need cannot occur until the system is operational and fielded.

One of the major roles of the human engineer is to determine the requirements and needs of the intended operators and users. Although reviewers such as representative users and operators or subject matter experts may be able to provide some feedback or requirements and functional descriptions, more effective feedback can be generated from

the review of proposed physical designs. The human engineer typically has responsibility for human-in-the-loop testing and user reviews. Through system use scenarios and static or dynamic models of system operation, the human engineer can elicit feedback that may be used for changes to designs or requirements. It is frequently useful for the systems engineers and other designers to participate in or observe user testing. Not all feedback will be relevant or valid. Changes to system design or requirements should be based on an objective analysis of information, not on the subjective preferences or opinions of reviewers. The human engineer will need to evaluate the feedback to determine what changes may be considered, and an initial estimate of the impact of those changes on other portions of the system should be made. This information will need to be passed to the systems engineers or other designers.

IEEE 1220-1998: *6.2.1 Compare to customer expectations*
6.5.11 – Develop models and fabricate prototypes
6.6.2 – Conduct verification evaluation
EIA-632: *Requirement 10 – Progress Against Requirements*
Requirement 11 – Technical Reviews
Requirement 19 – Specified Requirements
Requirement 20 – Implementation
Requirement 30 – Design Solution Verification
Requirement 31 – End Product Verification
Requirement 33 – End Products Validation
SE/SW CMM: *Requirements Development, SP 1.1-2 – Elicit Needs*
Requirements Development, SP 3.5-1 – Validate Requirements
Requirements Development, SP 3.5-2 – Validate Requirements with Comprehensive Methods
Technical Solution, SP 1.3-1 – Select Product Component Solutions
Validation, SP 1.1-1 – Establish a Validation Strategy
Validation, SP 1.2-2 – Establish the Validation Environment
Validation, SP 1.3-3 – Define Detailed Validation Procedures
Validation, SP 2.1-1 – Perform Validation
Validation, SP 2.2-1 – Capture and Analyze Validation Results
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C3.2.3.2 – T&E Guidelines
C3.6 – Operational Test & Evaluation (OT&E)
C5.2.3.3 – Design Synthesis and Verification
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
SE OSDs: *SE330 – Integrate System Physical Configuration*

3.8.3 Recommendation of Changes to Requirements or Designs

Deficiencies in system design that are revealed through verification or validation must be addressed by some combination of changes to the design and to requirements. These changes can frequently have far-reaching effects, leading to time delays and cost overruns. It is the role of the systems engineer to work to balance the required changes with the available resources to meet the design goals. This requires rapid feedback from

designers within various disciplines on the impact of changes. The systems engineer must consolidate this feedback and determine the best course of action.

The human engineer should go beyond singling out design deficiencies and should work to present alternative designs or requirements. No matter how extensive or accurate human engineering analyses may be, they are irrelevant and unusable if they cannot be translated into specific design solutions. In some cases, it may be found that the operators simply cannot meet the specified human performance requirements or that unsatisfactory workload levels exist. This will necessitate either a change to the requirements or an addition to the design to provide additional support. Proposed designs may conflict with requirements that have been specified by the human engineer. In some instances, other designers or the systems engineer may want to delete or ignore some derived requirements related to human engineering. The human engineer must know which human engineering requirements can be traded away to efficiently meet overall system requirements and which requirements cannot be sacrificed. The human engineer should not blindly hold to requirements to optimize human performance when the overall performance of the system will suffer.

Once deviations from requirements are noticed, the human engineer should estimate the impact on overall system performance and begin to develop a resolution to the problem. Since the systems engineering will be responsible for resolving conflicts, the proposed changes must have content and format useful to the systems engineer. The format of the suggestions should be identical or at least similar to that of suggestions provided by designers in other disciplines. The content of the suggestions needs to be sufficient to provide the systems engineer with a description of the changes, the rationale for the changes, and anticipated impacts on the remainder of the system.

IEEE 1220-1998: *6.7.1 – Assess requirement conflicts*
6.7.3 – Assess design alternatives
EIA-632: *Requirement 10 – Progress Against Requirements*
Requirement 11 – Technical Reviews
Requirement 19 – Specified Requirements
Requirement 23 – Tradeoff Analysis
SE/SW CMM: *Requirements Management, SP 1.3-1 – Manage Requirements Changes*
Verification, SP 3.2-2 – Analyze Verification Results and Identify Corrective Action
Verification, SP 3.3-1 – Perform Reverification
Validation, SP 2.2-1 – Capture and Analyze Validation Results
DoD 5000.2-R: *C2.8.5.5 – Human Factors Engineering*
C5.2.3.4 – System Analysis and Control
C5.2.3.5.9.1 – Human Factors Engineering (HFE)
SE OSDs: *SE330 – Integrate System Physical Configuration*

4 BIBLIOGRAPHY

Department of Defense, *Regulation 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs (MDAPs) and Major Automated Information System (MAIS) Acquisition Programs*, June 2001, Washington, DC.

Electronic Industries Alliance, *Processes for Engineering a System*, ANSI/EIA-632-1998, Jan 1999, EIA, Arlington, VA.

Institute of Electrical and Electronics Engineers, *Standard for Application and Management of the Systems Engineering Process*, IEEE 1220-1998, 22 Jan 1999, IEEE, New York, NY.

International Council on Systems Engineering, *Systems Engineering Handbook: A "How To" Guide for All Engineers, Release 1.0*, Jan 1998, INCOSE, Seattle, WA.

International Council on Systems Engineering, *Systems Engineering Handbook, Release 2.0*, in press, INCOSE, Seattle, WA.

Manning Affordability Initiative, *Human Engineering Process*, ONR/SC-21 Science and Technology Manning Affordability Initiative, http://www.manningaffordability.com/hse, Sep 1998, NSWCDD, Dahlgren, VA.

Software Engineering Institute, *CMMI^{SM} for Systems Engineering/Software Engineering/Integrated Product and Process Development*, CMMI^{SM} SE/SW v 1.02, Dec 2000, Pittsburgh, PA.

Wallace, D.F.; Winters, J.J.; and Lackie, J.H., "An Improved Operational Sequence Diagram Methodology for Use in System Development," in *Proceedings of the Human Factors and Ergonomics Society*, San Diego, CA, 2000, pp. 6-505 – 6-508.

Winters, J.J.; Parker, C.W.; Dugger, M.; Lackie, J.H.; and Wallace, D.F., "Advances in the Integration of Human Engineering and Systems Engineering," in *Proceedings of the Human Factors and Ergonomics Society*, San Diego, CA, 2000, pp. 6-481 – 6-484.

APPENDIX A

RELATIONSHIPS BETWEEN INTERACTIONS AND SYSTEMS ENGINEERING PUBLICATIONS

The following tables list the sections of this technical report that apply to individual sections of various systems engineering publications. For Tables A-1, A-2, A-3, A-4, and A-6, the relationships listed correspond to those provided at the end of each subsection in Section 3 of this technical report.

The following interactions in Table A-5 are based on the "Information for Milestone Reviews (DODI 5000.2)" chart that is included as Figure 1 in the current Defense Acquisition Management Framework. The interactions noted in the paper and in Appendix A are based on DoD 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs (MDAPs) and Major Automated Information System (MAIS) Acquisition Programs.

Table A-1. Interactions Sorted by IEEE 1220-1998

IEEE 1220-1998 Paragraph	Interaction Details Paragraph
6.1.2 Define project and enterprise constraints	3.1.1 Selection of Comparison Systems
	3.2.1 Human Engineering Constraints
	3.6.3 Development of Interface and Team Concepts or Designs
	3.7.2 Training Concept Evaluation
6.1.3 Define external constraints	3.1.1 Selection of Comparison Systems
	3.2.1 Human Engineering Constraints
	3.6.2 Selection of Human Interface and Team Guidelines
	3.6.3 Development of Interface and Team Concepts or Designs
	3.7.2 Training Concept Evaluation
6.1.4 Define operational scenarios	3.1.2 System Use Scenarios
6.1.7 Define interfaces	3.6.1 Points of Human Interface
	3.6.3 Development of Interface and Team Concepts or Designs
6.1.8 Define utilization environments	3.1.3 User Environment Characteristics and Effects
6.1.9 Define life cycle process concepts	3.7.2 Training Concept Evaluation
6.1.11 Define performance requirements	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
6.1.12 Define modes of operations	3.1.2 System Use Scenarios
6.1.14 Define design characteristics	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
6.1.15 Define human factors	3.2.1 Human Engineering Constraints
6.2.1 Compare to customer expectations	3.8.2 User Review
6.3.1 Functional context analysis	3.3.1 Functional Decomposition
6.3.1.2 Define functional interfaces	3.6.1 Points of Human Interface
6.3.2 Functional decomposition	3.3.1 Functional Decomposition
6.3.2.4 Define data and control flows	3.6.2 Selection of Human Interface and Team Guidelines
	3.6.3 Development of Interface and Team Concepts or Designs
6.3.3 Establish functional architecture	3.3.2 Review of Functional Architecture
6.4 Functional verification	3.3.2 Review of Functional Architecture
6.5.1 Group and allocate functions	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
6.5.2 Identify design solution alternatives	3.5.1 Development of the Task List
	3.5.2 Identification of Task Characteristics, Interactions, and Sequences
	3.5.3 Selection of Modeling Tools and Techniques
6.5.4 Assess life cycle quality factors	3.7.2 Training Concept Evaluation

Table A-1. Interactions Sorted by IEEE 1220-1998 (Continued)

IEEE 1220-1998 Paragraph	Interaction Details Paragraph
6.5.5 Assess technology requirements	3.4.1 Consideration of Human Engineering Technologies
6.5.7 Define physical interfaces	3.5.4 Task and Function Audit
	3.6.1 Points of Human Interface
	3.6.3 Development of Interface and Team Concepts or Designs
6.5.11 Develop models and fabricate prototypes	3.4.1 Consideration of Human Engineering Technologies
	3.5.3 Selection of Modeling Tools and Techniques
	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.2 User Review
6.5.15 Final design	3.5.4 Task and Function Audit
	3.7.1 Individual and Team Workload and Performance Estimation
6.6.2 Conduct verification evaluation	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
6.7 Systems analysis	3.7.3 Tradeoff of Concepts and Designs
6.7.1 Assess requirement conflicts	3.8.3 Recommendation of Changes to Requirements or Designs
6.7.3 Assess design alternatives	3.8.3 Recommendation of Changes to Requirements or Designs
6.7.5 Define trade-study scope	3.7.3 Tradeoff of Concepts and Designs

Table A-2. Interactions Sorted by EIA 632

EIA-632 Requirement	Interaction Details Paragraph
Planning Process	
Requirement 4 – Process Implementation Strategy	3.1.1 Selection of Comparison Systems
	3.1.2 System Use Scenarios
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
Requirement 5 – Technical Effort Definition	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.4.1 Consideration of Human Engineering Technologies
	3.5.3 Selection of Modeling Tools and Techniques
Assessment Process	
Requirement 10 – Progress Against Requirements	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.2 User Review
	3.8.3 Recommendation of Changes to Requirements or Designs
Requirement 11 – Technical Reviews	3.8.2 User Review
	3.8.3 Recommendation of Changes to Requirements or Designs
Control Process	
Requirement 13 – Information Dissemination	3.1.1 Selection of Comparison Systems
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.5.3 Selection of Modeling Tools and Techniques
Requirements Definition Process	
Requirement 14 – Acquirer Requirements	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
Requirement 15 – Other Stakeholder Requirements	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
Requirement 16 – System Technical Requirements	3.1.2 System Use Scenarios
	3.1.3 User Environment Characteristics and Effects
	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.4.1 Consideration of Human Engineering Technologies
Solution Definition Process	
Requirement 17 – Logical Solution Representations	3.3.1 Functional Decomposition
	3.3.2 Review of Functional Architecture
	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
	3.5.1 Development of the Task List
	3.5.2 Identification of Task Characteristics, Interactions, and Sequences
	3.5.4 Task and Function Audit

Table A-2. Interactions Sorted by EIA 632 (Continued)

EIA-632 Requirement	Interaction Details Paragraph
Requirement 18 – Physical Solution Representations	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
	3.5.1 Development of the Task List
	3.5.2 Identification of Task Characteristics, Interactions, and Sequences
	3.5.4 Task and Function Audit
	3.6.1 Points of Human Interface
	3.6.2 Selection of Human Interface and Team Guidelines
	3.6.3 Development of Interface and Team Concepts/Designs
	3.7.3 Tradeoff of Concepts and Designs
Requirement 19 – Specified Requirements	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
	3.8.3 Recommendation of Changes to Requirements or Designs
Implementation Process	
Requirement 20 – Implementation	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
Transition to Use Process	
Requirement 21 – Transition to Use	3.7.2 Training Concept Evaluation
Systems Analysis Process	
Requirement 23 – Tradeoff Analysis	3.5.3 Selection of Modeling Tools and Techniques
	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.3 Tradeoff of Concepts and Designs
	3.8.3 Recommendation of Changes to Requirements or Designs
Requirement 24 – Risk Analysis	3.1.2 System Use Scenarios
	3.1.3 User Environment Characteristics and Effects
Requirements Validation Process	
Requirement 25 – Requirement Statements Validation	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
Requirement 26 – Acquirer Requirements Validation	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
Requirement 27 – Other Stakeholder Requirements Validation	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
Requirement 28 – System Technical Requirements Validation	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
Requirement 29 – Logical Solution Representations Validation	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.1 Comparison to Human Engineering Requirements
System Verification Process	
Requirement 30 – Design Solution Verification	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
Requirement 31 – End Product Verification	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
End Products Validation Process	
Requirement 33 – End Products Validation	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review

Table A-3. Interactions Sorted by SEI CMMI SE/SW v 1.02, Engineering Process Area

CMMI Goal and Practice	Interaction Details Paragraph
Requirements Management, SG 1: Manage Requirements	
SP 1.1-1 – Obtain an Understanding of Requirements	3.1.1 Selection of Comparison Systems
	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
SP 1.2-2 – Obtain Commitment to Requirements	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
SP 1.3-1 – Manage Requirements Changes	3.8.3 Recommendation of Changes to Requirements or Designs
Requirements Development, SG 1: Develop Customer Requirements	
SP 1.1-1 – Collect Stakeholder Needs	3.1.2 System Use Scenarios
	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.7.2 Training Concept Evaluation
SP 1.1-2 – Elicit Needs	3.1.2 System Use Scenarios
	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.7.2 Training Concept Evaluation
	3.8.2 User Review
SP 1.2-1 – Transform Stakeholder Needs, Expectations, Constraints, and Interfaces into Customer Requirements	3.1.2 System Use Scenarios
	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.7.2 Training Concept Evaluation
Requirements Development, SG 2: Develop Product Requirements	
SP 2.1-1 – Establish Product and Product Component Requirements	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.6.2 Selection of Human Interface and Team Guidelines
SP 2.2-1 – Allocate Product Component Requirements	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
SP 2.3-1 – Identify Interface Requirements	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.4.1 Consideration of Human Engineering Technologies
	3.6.1 Points of Human Interface
Requirements Development, SG 3: Analyze and Validate Requirements	
SP 3.1-1 – Establish Operational Concepts and Scenarios	3.1.2 System Use Scenarios
	3.7.2 Training Concept Evaluation
SP 3.2-1 – Establish a Definition of Required Functionality	3.3.1 Functional Decomposition
	3.3.2 Review of Functional Architecture

Table A-3. Interactions Sorted by SEI CMMI SE/SW v 1.02, Engineering Process Area (Continued)

CMMI Goal and Practice	Interaction Details Paragraph
SP 3.3-1 – Analyze Requirements	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
SP 3.4-3 – Evaluate Product Cost, Schedule, and Risk	3.4.1 Consideration of Human Engineering Technologies
	3.7.2 Training Concept Evaluation
SP 3.5-1 – Validate Requirements	3.1.3 User Environment Characteristics and Effects
	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.2 User Review
SP 3.5-2 – Validate Requirements with Comprehensive Methods	3.1.2 System Use Scenarios
	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.2 User Review
Technical Solution, SG 1: Select Product Component Solutions	
SP 1.1-1 – Develop Alternative Solutions and Selection Criteria	3.1.1 Selection of Comparison Systems
	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
	3.6.3 Development of Interface and Team Concepts/Designs
SP 1.1-2 – Develop Detailed Alternative Solutions and Selection Criteria	3.1.2 System Use Scenarios
	3.4.1 Consideration of Human Engineering Technologies
	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
	3.5.1 Development of the Task List
	3.6.3 Development of Interface and Team Concepts/Designs
SP 1.2-2 – Evolve Operational Concepts and Scenarios	3.1.2 System Use Scenarios
	3.1.3 User Environment Characteristics and Effects
	3.5.1 Development of the Task List
	3.5.2 Identification of Task Characteristics, Interactions, and Sequences
	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.2 Training Concept Evaluation
SP 1.3-1 – Select Product Component Solutions	3.4.1 Consideration of Human Engineering Technologies
	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.3 Tradeoff of Concepts and Designs
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
Technical Solution, SG 2: Develop the Design	
SP 2.1-1 – Use Effective Design Methods	3.5.3 Selection of Modeling Tools and Techniques
	3.5.4 Task and Function Audit
	3.6.2 Selection of Human Interface and Team Guidelines
	3.7.1 Individual and Team Workload and Performance Estimation

Table A-3. Interactions Sorted by SEI CMMI SE/SW v 1.02, Engineering Process Area (Continued)

CMMI Goal and Practice	Interaction Details Paragraph
SP 2.2-1 – Develop a Technical Data Package	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.6.3 Development of Interface and Team Concepts/Designs
	3.7.3 Tradeoff of Concepts and Designs
SP 2.2-3 – Establish a Complete Technical Data Package	3.1.2 System Use Scenarios
	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.5.1 Development of the Task List
	3.5.2 Identification of Task Characteristics, Interactions, and Sequences
	3.6.3 Development of Interface and Team Concepts/Designs
	3.7.3 Tradeoff of Concepts and Designs
SP 2.3-1 – Establish Interface Descriptions	3.4.1 Consideration of Human Engineering Technologies
	3.6.1 Points of Human Interface
	3.6.3 Development of Interface and Team Concepts/Designs
SP 2.3-3 – Design Comprehensive Interface	3.6.1 Points of Human Interface
	3.6.3 Development of Interface and Team Concepts/Designs
	3.7.1 Individual and Team Workload and Performance Estimation
SP 2.3-4 – Perform Make, Buy, or Reuse Analyses	3.4.1 Consideration of Human Engineering Technologies
	3.7.2 Training Concept Evaluation
Technical Solution, SG 3: Implement the Product Design	
SP 3.1-1 – Implement the Design	3.6.2 Selection of Human Interface and Team Guidelines
SP 3.2-1 – Establish Product Support Documentation	3.7.2 Training Concept Evaluation
Product Integration, SG 1: Prepare for Product Integration	
SP 1.1-1 – Establish a Product Integration Strategy	3.2.1 Human Engineering Constraints
	3.7.2 Training Concept Evaluation
SP 1.2-2 – Establish the Product Integration Environment	3.1.3 User Environment Characteristics and Effects
	3.7.2 Training Concept Evaluation
SP 1.3-3 – Define Detailed Product Integration Procedures	3.7.2 Training Concept Evaluation
Product Integration, SG 2: Ensure Interface Compatibility	
SP 2.1-1 – Review Interface Descriptions for Completeness	3.6.3 Development of Interface and Team Concepts/Designs
Product Integration, SG 3: Assemble Product Components and Deliver the Product	
SP 3.3-1 – Checkout Assembled Product Components	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.2 Training Concept Evaluation
Verification, SG 1: Prepare for Verification	
SP 1.1-1 – Establish a Verification Strategy	3.1.3 User Environment Characteristics and Effects
	3.5.3 Selection of Modeling Tools and Techniques
	3.6.2 Selection of Human Interface and Team Guidelines
	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements

Table A-3. Interactions Sorted by SEI CMMI SE/SW v 1.02, Engineering Process Area (Continued)

CMMI Goal and Practice	Interaction Details Paragraph
SP 1.2-2 – Establish the Verification Environment	3.1.2 System Use Scenarios
	3.1.3 User Environment Characteristics and Effects
	3.5.3 Selection of Modeling Tools and Techniques
	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
SP 1.3-3 – Establish Detailed Verification Plans	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
Verification, SG 2: Perform Peer Reviews	
SP 2.1-1 – Prepare for Peer Reviews	3.3.2 Review of Functional Architecture
	3.5.4 Task and Function Audit
	3.7.3 Tradeoff of Concepts and Designs
SP 2.2-1 – Conduct Peer Reviews	3.3.2 Review of Functional Architecture
	3.5.4 Task and Function Audit
	3.7.3 Tradeoff of Concepts and Designs
SP 2.3-2 – Analyze Peer Review Data	3.3.2 Review of Functional Architecture
	3.5.4 Task and Function Audit
	3.7.3 Tradeoff of Concepts and Designs
Verification, SG 3: Verify Selected Work Products	
SP 3.1-1 – Perform Verification	3.5.4 Task and Function Audit
	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
SP 3.2-2 – Analyze Verification Results and Identify Corrective Action	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.3 Tradeoff of Concepts and Designs
	3.8.1 Comparison to Human Engineering Requirements
	3.8.3 Recommendation of Changes to Requirements or Designs
SP 3.3-1 – Perform Reverification	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
	3.8.3 Recommendation of Changes to Requirements or Designs
Validation, SG 1: Prepare for Validation	
SP 1.1-1 – Establish a Validation Strategy	3.1.3 User Environment Characteristics and Effects
	3.5.3 Selection of Modeling Tools and Techniques
	3.6.2 Selection of Human Interface and Team Guidelines
	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
SP 1.2-2 – Establish the Validation Environment	3.1.2 System Use Scenarios
	3.1.3 User Environment Characteristics and Effects
	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
SP 1.3-3 – Define Detailed Validation Procedures	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review

Table A-3. Interactions Sorted by SEI CMMI SE/SW v 1.02, Engineering Process Area (Continued)

CMMI Goal and Practice	Interaction Details Paragraph
Validation, SG 2: Validate Product or Product Components	
SP 2.1-1 – Perform Validation	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
SP 2.2-1 – Capture and Analyze Validation Results	3.7.1 Individual and Team Workload and Performance Estimation
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
	3.8.3 Recommendation of Changes to Requirements or Designs

Table A-4. Interactions Sorted by DoD 5000.2-R (June 2001)

DoD 5000.2-R	Interaction Details Paragraph
C1.2 Thresholds and Objectives	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
C1.3.3 Cost/Schedule/Performance Tradeoffs	3.7.3 Tradeoff of Concepts and Designs
C1.4 Acquisition Program Baseline (APB)	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
C2.2 Requirements	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
C2.7.2 Interoperability	3.2.1 Human Engineering Constraints
C2.8.5 Human Systems Integration (HSI)	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.1 Comparison to Human Engineering Requirements
C2.8.5.2 Personnel	3.7.2 Training Concept Evaluation
C2.8.5.3 Training	3.7.2 Training Concept Evaluation
C2.8.5.4 Personnel Survivability and Habitability	3.1.3 User Environment Characteristics and Effects
	3.3.2 Review of Functional Architecture
C2.8.5.5 Human Factors Engineering	3.1.2 System Use Scenarios
	3.1.3 User Environment Characteristics and Effects
	3.4.1 Consideration of Human Engineering Technologies
	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
	3.6.1 Points of Human Interface
	3.6.2 Selection of Human Interface and Team Guidelines
	3.6.3 Development of Interface and Team Concepts or Designs
	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.2 Training Concept Evaluation
	3.8.2 User Review
	3.8.3 Recommendation of Changes to Requirements or Designs
C2.8.6 Environment, Safety, and Occupational Health (ESOH) Considerations	3.1.3 User Environment Characteristics and Effects
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.1 Comparison to Human Engineering Requirements
C3.2.3.2 T&E Guidelines	3.1.2 System Use Scenarios
	3.8.2 User Review
C3.4 Developmental Test and Evaluation (DT&E)	3.4.1 Consideration of Human Engineering Technologies
	3.7.3 Tradeoff of Concepts and Designs
C3.6 Operational Test & Evaluation (OT&E)	3.8.2 User Review
C4.2 Analysis of Multiple Concepts	3.7.3 Tradeoff of Concepts and Designs
C4.4 Affordability	3.2.1 Human Engineering Constraints
C4.5.4 Manpower	3.2.1 Human Engineering Constraints

Table A-4. Interactions Sorted by DoD 5000.2-R (Continued)

DoD 5000.2-R	Interaction Details Paragraph
C5.2 Systems Engineering	3.1.1 Selection of Comparison Systems
	3.5.4 Task and Function Audit
	3.6.1 Points of Human Interface
C5.2.3.1 Requirements Analysis	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
C5.2.3.2 Functional Analysis/Allocation	3.3.1 Functional Decomposition
	3.3.2 Review of Functional Architecture
	3.4.2. Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
C5.2.3.3 Design Synthesis and Verification	3.6.3 Development of Interface and Team Concepts or Designs
	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.2 Training Concept Evaluation
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
C5.2.3.4 System Analysis and Control	3.7.3 Tradeoff of Concepts and Designs
	3.8.3 Recommendation of Changes to Requirements or Designs
C5.2.3.5.2 Modeling and Simulation (M&S)	3.7.1 Individual and Team Workload and Performance Estimation
C5.2.3.5.2.3 Planning the M&S Approach	3.5.3 Selection of Modeling Tools and Techniques
C5.2.3.5.2.4 M&S Standards	3.5.3 Selection of Modeling Tools and Techniques
C5.2.3.5.2.6 M&S Support of SBA	3.1.2 System Use Scenarios
C5.2.3.5.4.4 Support Resources	3.7.2 Training Concept Evaluation
C5.2.3.5.5 Open Systems Design	3.6.1 Points of Human Interface
	3.6.2 Selection of Human Interface and Team Guidelines
C5.2.3.5.9 Human Systems Integration (HSI)	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.1 Comparison to Human Engineering Requirements
C5.2.3.5.9.1 Human Factors Engineering (HFE)	3.1.2 System Use Scenarios
	3.1.3 User Environment Characteristics and Effects
	3.4.1 Consideration of Human Engineering Technologies
	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
	3.5.1 Development of the Task List
	3.5.2 Identification of Task Characteristics, Interactions, and Sequences
	3.6.1 Points of Human Interface
	3.6.2 Selection of Human Interface and Team Guidelines
	3.6.3 Development of Interface and Team Concepts or Designs
	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.2 Training Concept Evaluation
	3.8.2 User Review
	3.8.3 Recommendation of Changes to Requirements or Designs

Table A-4. Interactions Sorted by DoD 5000.2-R (Final Coordination Draft) (Continued)

DoD 5000.2-R	Interaction Details Paragraph
C5.2.3.5.9.2 Habitability and Personnel Survivability	3.1.3 User Environment Characteristics and Effects
	3.3.2 Review of Functional Architecture
C5.2.3.5.9.3 Manpower Initiatives	3.7.1 Individual and Team Workload and Performance Estimation
C5.2.3.5.9.4 Personnel Initiatives	3.7.2 Training Concept Evaluation
C5.2.3.5.9.5 Training	3.7.2 Training Concept Evaluation
C5.2.3.5.10 Environment, Safety, and Occupational Health (ESOH)	3.1.3 User Environment Characteristics and Effects
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.1 Comparison to Human Engineering Requirements
C7.5 Technology Maturity	3.4.1 Consideration of Human Engineering Technologies

Table A-5. Interactions Sorted by Products from DoD 5000.2

DoD 5000.2 Products	Interaction Details Paragraph
Acquisition Program Baseline	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
Acquisition Strategy	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.4.1 Consideration of Human Engineering Technologies
Affordability Assessment	3.2.1 Human Engineering Constraints
Analysis of Alternatives	3.7.3 Tradeoff of Concepts and Designs
Beyond Low Rate Initial Production (LRIP) Report	3.8.1 Comparison to Human Engineering Requirements
Independent Technology Assessment	3.4.1 Consideration of Human Engineering Technologies
Live Fire T&E Report	3.8.1 Comparison to Human Engineering Requirements
Manpower Estimate	3.6.3 Development of Human Interface and Team Concepts or Designs
	3.7.1 Individual and Team Workload and Performance Estimation
Market Research	3.4.1 Consideration of Human Engineering Technologies
Mission Need Statement	3.1.2 System Use Scenarios
Operational Requirements Document	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.8.1 Comparison to Human Engineering Requirements
Operational Test & Evaluation (OT&E) Results	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
Postdeployment Performance Review	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review
Test & Evaluation Master Plan	3.1.2 System Use Scenarios
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.5.3 Selection of Modeling Tools and Techniques
	3.8.1 Comparison to Human Engineering Requirements
	3.8.2 User Review

Table A-6. Interactions Sorted by Systems Engineering OSDs

Systems Engineering OSD	Interaction Details Paragraph
SE110 – Define and Assess Operational Environment	3.1.1 Selection of Comparison Systems
	3.1.2 System Use Scenarios
	3.1.3 User Environment Characteristics and Effects
SE130 – Identify Constraints and Analyze Operational Requirements	3.2.1 Human Engineering Constraints
	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
	3.6.2 Selection of Human Interface and Team Guidelines
	3.6.3 Development of Interface and Team Concepts or Designs
	3.7.2 Training Concept Evaluation
SE140 – Identify Functional and Performance Requirements	3.2.2 Human Performance Requirements and Human Engineering Design Requirements
SE210 – Functional Definition	3.3.1 Functional Decomposition
	3.3.2 Review of Functional Architecture
	3.6.1 Points of Human Interface
SE310 – Synthesize Multiple Physical Architectures	3.4.1 Consideration of Human Engineering Technologies
	3.4.2 Early Identification of Mandatory Allocations
	3.4.3 Development and Approval of Function Allocation Recommendations
	3.8.1 Comparison to Human Engineering Requirements
SE320 – Evaluate and Select Preferred Architecture	3.5.1 Development of the Task List
	3.5.2 Identification of Task Characteristics, Interactions, and Sequences
	3.5.3 Selection of Modeling Tools and Techniques
	3.5.4 Task and Function Audit
	3.6.1 Points of Human Interface
	3.7.1 Individual and Team Workload and Performance Estimation
	3.7.3 Tradeoff of Concepts and Designs
SE330 – Integrate System Physical Configuration	3.5.3 Selection of Modeling Tools and Techniques
	3.8.2 User Review
	3.8.3 Recommendation of Changes to Requirements or Designs

Note*: Systems Engineering and Human Engineering operational sequence diagrams are available at* http://www.manningaffordability.com. *URLs for direct access are:*
SE OSDs: http://www.manningaffordability.com/S&tweb/PUBS/SE_HE/SE_OSD.pdf
HE OSDs: http://www.manningaffordability.com/S&tweb/PUBS/SE_HE/HE_OSD.pdf

APPENDIX B

SUGGESTED REFERENCES

The following references each provide further information on human engineering or human factors, primarily in the context of systems engineering.

Human Factors in Systems Engineering; Alphonse Chapanis; 1996 (340 pages).
Part of a series of titles on systems engineering, this book covers the integration of human factors into the development of tools, machines, and systems. It includes sections on systems engineering and systems engineering work products along with human factors methods. General introductions to human physical and mental characteristics and personnel selection and training issues are also included. The conclusion of the book covers the specification of human-system requirements and how to make tradeoffs between competing requirements or designs.

MANPRINT: An Approach to Systems Integration; Harold Booher, Ed.; 1990 (600 pages).
This book is a collection of chapters by various authors on topics relating to the Manpower and Personnel Integration (MANPRINT) program developed for the U.S. Army. Management, design, and integration topics are included. Although sections such as those on design tools lack up-to-date information, the discussion of the principles of human engineering and integration remains relevant.

Introduction to Human Factors Engineering; Christopher Wickens, Sallie Gordon, and Yili Liu; 1997 (750 pages).
Although there is an emphasis on cognition and human information processing, this book provides a broad coverage of human factors issues. Topics include automation, human-computer interaction, safety, and workplace layout.

Human Factors in Engineering and Design (7th ed.); Mark Sanders and Ernest McCormick; 1993 (790 pages).
First published in 1957, this book is commonly used as an upper-undergraduate level or introductory graduate level textbook. It provides a broad overview of human factors and ergonomics topics and sections on how human factors should be applied. Other sections include information input, human output and control, workplace design, and environmental conditions. Information included on human-computer interaction is relatively dated, but the principles illustrated by the examples included remain applicable.

Human Performance Engineering (3rd ed.); Robert Bailey; 1996 (576 pages).
Although sometimes billed as a general human factors reference, this book places significant emphasis on computer-based systems. There is more of a discussion on human factors techniques and methodologies than in other general texts. Design and analysis examples are included, as are several real-world examples of violations of human factors principles.

System Design and Evaluation; Sara Czaja; 1997. In G. Salvendy (Ed.), **Handbook of Human Factors and Ergonomics** (2nd ed.) (pp.17-40).
This book chapter provides a brief overview of system design and presents a discussion of different approaches to system design that address the presence and role of humans

within the system. The basic human factors activities in system design and test and evaluation are also described.

Allocation of Functions; Joseph Sharit; 1997. In G. Salvendy (Ed.), **Handbook of Human Factors and Ergonomics** (2nd ed.) (pp. 301-339).
Part of a section on job design, this book chapter discusses the importance of human-machine allocation of functions during system design. Different procedures for function allocation are covered, as are implications for dynamic allocation – the transfer of functions between humans and machines during system operation. The issues of trust and confidence in automated systems are also covered.

DISTRIBUTION

	Copies
DOD ACTIVITIES (CONUS)	
ATTN CODE A76 (TECHNICAL LIBRARY) COMMANDING OFFICER CSSDD NSWC 6703 W HIGHWAY 98 PANAMA CITY FL 32407-7001	1
DEFENSE TECHNICAL INFO CENTER 8725 JOHN J KINGMAN ROAD SUITE 0944 FT BELVOIR VA 22060-6218	2
ATTN MATT HENRY ASSISTANT DCNO (M&P) FOB2 NAVY ANNEX WASHINGTON DC 20370	1
ATTN GREG MAXWELL SEA 03 1333 ISAAC HULL AVENUE SE BLDG 197 RM 2W-2830 WASHINGTON NAVY YARD WASHINGTON DC 20376	1
ATTN BOB BOST SEA 03 TD 1333 ISAAC HULL AVENUE SE STOP 2201 BLDG 197 ROOM 3W-1241 WASHINGTON NAVY YARD WASHINGTON DC 20376-2201	1
ATTN DICK VOGELSONG 1333 ISAAC HULL AVENUE SE BLDG 197 RM 1214 WASHINGTON NAVY YARD WASHINGTON DC 20376	1
ATTN LAWRENCE ROGERS PEO(IWS) BLDG 197 RM 1W-3923 WASHINGTON NAVY YARD WASHINGTON DC 20376	1
ATTN PETE BROWN 1333 ISAAC HULL AVE WASHINGTON NAVY YARD WASHINGTON DC 20376	1

	Copies
ATTN GWENDOLYN CAMPBELL COMMANDING OFFICER NAVAIR ORL TSD CODE 4961 12350 RESEARCH PARKWAY ORLANDO FL 32826-3224	1
ATTN JAMES PHARMER COMMANDING OFFICER NAVAIR ORL TSD CODE 4961 12350 RESEARCH PARKWAY ORLANDO FL 32826-3224	1
ATTN CAPT MIKE WANJON OFFICE OF CHIEF OF NAVAL OPERATIONS 2 NAVY ANNEX CODE N125 WASHINGTON DC 20370	1
ATTN HAL GUARD OFFICE OF NAVAL RESEARCH 800 N QUINCY STREET ARLINGTON VA 22217-5660	1
ATTN JUDY WYNE OFFICE OF NAVAL RESEARCH 800 N QUINCY STREET ARLINGTON VA 22217-5660	1
NON-DOD ACTIVITIES (CONUS)	
ATTN DOCUMENT CENTER THE CNA CORPORATION 4825 MARK CENTER DRIVE ALEXANDRIA VA 22311-1850	1
ATTN JOHN WINTERS BASIC COMMERCE & INDUSTRIES P O BOX 1748 DAHLGREN VA 22448	3
ATTN JOHN LACKIE SONALYSTS INC P O BOX 1839 DAHLGREN VA 22448	1

DISTRIBUTION (Continued)

		Copies
INTERNAL		
B05	HARRY CRISP	1
B60	TECHNICAL LIBRARY	3
N05	REUBEN PITTS	1
N05M	TRISH HAMBURGER	4
N93	DENNIS WHITE	1
T20	JOHN BURROW	1